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THERMAL ICE PRESSURES ON DAMS: A LITERATURE STUDY

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ABSTRACT

Rising temperatures can cause the thermal expansion of an ice sheet covering a reservoir and exert significant pressure on hydraulic structures such as dams. The design method currently used appears inappropriate as it fails to consider the complexity of the problem. Empirical and theoretical methods have been developed to predict ice pressures. This report looks at some of these methods of predicting ice pressures. Attempts have also been made using these models to predict the pressures that might be expected at dams in the Sudbury, North Bay and Muskoka areas. The unique properties of ice are also discussed.

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THERMAL ICE PRESSURES ON DAMS: A LITERATURE STUDY

1.0 INTRODUCTION

The thermal expansion of a restrained ice sheet covering a reservoir can cause a considerable horizontal thrust on the face of a dam. In the past, the design thrust value was based upon the crushing strength of ice which gave values of 50 kips/linear foot or greater across the dam face. Realization of the creep behaviour of ice lead to further investigations and a value of 10 kips/linear foot became a North American "standard", based upon research done in the late 1940's/1/.

Although there are few, if any, reported failures of dams due to ice forces, this standard value is considered to be too general for all dams. Ice thrusts are a function of meteorologic and other conditions which vary from site to site. Ice thrusts that have been measured or back calculated from failures and published by others indicate that the commonly used standard is inappropriate. This is shown in Figure 1/1/. Therefore, a rational approach that takes the factors controlling ice thrust development into consideration is desired.

Several methods have been proposed for the prediction of thermal ice thrusts. These methods vary from extrapolating laboratory and field data to numerical models for ice behaviour. A discussion of some of these methods is included in this report.

A common shortcoming of all of these methods is their lack of validation. Some methods have not been compared to field measurements. Other methods have been compared to field measurements, however, the comparisons are very limited and therefore questionable. Reasons for the lack of validation include the inherent problems involved in the measurement of ice forces due to the unique properties of ice and the lack of published data from field measurements.

This report includes an examination of some of the methods available for predicting ice thrust development. Two of these methods were used to determine the ice thrusts that would be expected at dams in three areas of Ontario. The three areas of interest were: Sudbury, North Bay, and the Muskoka River. Meteorologic data for these three locations was obtained from Environment Canada and some estimations of ice thrusts were made. During this study it was found that there are still many uncertainties with respect to ice behaviour and the estimation of thermal ice forces. Therefore, this report also includes a general discussion of the factors affecting the development, prediction, and measurement of thermal ice forces as well as recommendations for future research.

2.0 THERMAL EXPANSION OF ICE

Thermal ice forces are those developed when a restrained ice sheet is subjected to rising temperatures, causing it to expand laterally. Strain (ε) due to thermal expansion of ice is expressed as a function of the temperature change of the ice ($\Delta\theta$) and the coefficient of thermal expansion (α) of ice, and is given as:

$$\varepsilon = (\Delta\theta)(\alpha) \qquad (1)$$

This strain can result in significant stresses in a confined ice sheet since the crushing strength of ice can be 50 kips/ linear foot.

The coefficient of thermal expansion for ice is a function of ice temperature and is given by the relationship/1/:

$$\alpha = (54 + 0.18\theta) \times 10^{-6} \text{ per } ^\circ\text{C of rise}$$

where θ is the ice temperature in degrees Celsius. For most applications,the use of $\alpha = 50 \times 10^{-6}\ ^\circ\text{C}^{-1}$ is a suitable approximation.

As an example, this would mean that a round, 1 kilometre diameter, ice sheet subject to a 10°C temperature rise would expand diametrically by 0.5 metres . In a confined area such as a headpond, a lateral expansion of this magnitude could exert considerable force on the surrounding shoreline and any hydraulic structures. This phenomenon is particularly important when one considers that ice forces on smaller dams may exceed the hydrostatic pressures that they were designed to withstand.

2.1 Modelling Ice Thrust

Two distinct problems occur when trying to model thermal ice forces. The first problem involves the prediction of the temperature distribution within the ice sheet as a function of the ice properties and meteorological variables. The second problem involves the determination of the stresses developed within the ice sheet due to changes in temperature. Further problems are encountered when trying to measure ice properties and ice forces for use in the models and in the validation of the models. These problems are caused by the

unique temperature and time-dependent stress-strain behaviour of ice. Each of these problems is discussed below.

2.1.1 Temperature Distribution Within an Ice Sheet

While the relationship describing the thermal expansion of ice due to an increase in temperature is quite straightforward, the determination of the temperature change of the ice is extremely difficult. The model commonly used to determine the heat flow and temperature distribution within the ice sheet is the one dimensional heat flow equation which is given as/2/:

$$\frac{\delta\theta}{\delta t} = H^2 \frac{\delta^2\theta}{\delta x^2} \qquad (2)$$

where θ is the temperature of the ice, t is time, H is the coefficient of diffusivity of the ice (which is a function of the conductivity, heat capacity and density of the ice), and x is the distance from the lower ice surface.

The temperature within the ice sheet is initially assumed to be linear, varying from some temperature at the upper surface to 0°C at the lower (ice/water) interface. The temperature at the upper surface and within the ice sheet, however, can vary over a wide range due to several factors. Air temperature, wind speed, solar radiation, ice thickness, varying thermal properties of the ice, snow cover and other factors all affect temperature fluctuations within the ice sheet and at its upper surface. Determination of all of these factors and their effects on the temperature distribution within the ice sheet is very difficult. There is also a lack of thorough field work in which both the meteorologic data and temperature measurements for the entire thickness of the ice sheet have been recorded. This has hindered the correlation of prediction models with actual field values.

Care must also be taken to understand the boundary conditions and the method used to solve the heat flow equation. Several authors/3,4/ have suggested that Drouin and Michel/2/ made an error in their solution of the heat flow equation. This is discussed later in the section describing the method of Drouin and Michel.

Ice also exhibits different thermal properties at different temperatures as shown in Table I/3/. This serves to further complicate the problem as different layers within the ice sheet will have different thermal properties.

2.1.2 Stress Development Within an Ice Sheet

Even if the temperature changes within the ice sheet can be quantified accurately, the determination of the stresses developed due to expansion remains difficult. Ice is a unique material; it exists in nature at a temperature very close to its melting point and has a distinct crystal structure. This causes it to exhibit a time dependent elastic-plastic stress-strain

relationship, as shown in Figure 2 /2/. This behaviour is generally described by a rheological equation which has terms to describe both the elastic and time-dependent plastic behaviour.

The parameters that define the elastic ice behaviour are also dependent upon the duration, orientation, and rate of loading, and the ice temperature. These properties of ice have only served to complicate the already difficult task of predicting the thermal stresses developed within an ice sheet.

Prediction is often done by extrapolation of laboratory test results or by solving a rheological equation for ice.

2.2 Factors Influencing Ice Thrust

The following factors have an influence on the magnitude of thermal ice thrusts. For most ice modelling, many of these factors have to be ignored in order to get solutions. This need to simplify the problem is another reason why models are often inaccurate.

2.2.1 Starting Temperature

In the determination of the magnitude of thermal ice forces, the initial temperature of the ice is an important factor. Results of laboratory tests on ice specimens have shown that, for a given temperature rise or rate of temperature rise, the lower the initial temperature, the greater the magnitude of the thermal ice force that develops. This effect can be seen in Figure 3/2/.

2.2.2 Rate of Temperature Increase

The relationship between the rate of temperature increase of the ice and its effect on the magnitude of the force that is developed has been a point of some confusion. The strain (ε) of the ice is related to the temperature change of the ice ($\Delta\theta$) and the coefficient of thermal expansion of ice (α), as shown previously in Equation 1.

Differentiating this equation with respect to time yields a relationship between strain rate and the rate of temperature rise of the ice. The more rapid the temperature rise, the greater the strain rate. A rapid straining of the ice sheet would result in high stresses as the ice would have little chance to deform plastically. Ice temperature change, however, is not directly related to air temperature change.

The relationship between air temperature change, ice temperature change, and stresses developed in an ice sheet has resulted in two distinct theories. Most authors agree that there is a ceiling to the effect that the rate of temperature increase can have on the stresses developed. This upper limit is due to the creep of the ice in the upper section of the sheet before the thermal "wave" is able to propagate into the lower section of the ice sheet. Drouin and Michel/2,5/, however, believe that a given temperature rise over a long time period will cause the greatest pressure as opposed to the same temperature change over a

shorter time period. Bergdahl and Wernersson/4,6/ argue that the more rapid the temperature rise, the greater the pressure that will be developed.

This latter theory appears to be more likely. Field and laboratory measurements have shown that thermal ice pressures develop quite rapidly upon warming of the ice. Monfore's laboratory work has indicated that greater rates of temperature rise resulted in greater pressures being developed, as shown in Figure 3/2/. It has been suggested that Drouin and Michel made an error in their work that resulted in their strange temperature-pressure theory. This is discussed later in the section describing the method of Drouin and Michel. For future work it is recommended that the relationship between air temperature change and ice temperature change of Bergdahl and Wernersson be used, as opposed to that of Drouin and Michel. Therefore, for this study, rapid temperature change is assumed to result in a rapid pressure increase and the development of the maximum thrust.

2.2.3 Solar Radiation

The influx of solar radiation can have a pronounced effect on the magnitude of the forces that develop. Incident solar radiation causes an increase in both the rate and magnitude of the temperature increase of the ice sheet. This can cause greater stresses to be developed as shown in Figure 4/5/.

2.2.4 Snow Cover

Whether or not snow cover exists on the ice sheet can greatly influence the development of thermal ice forces. Due to the thermal properties of snow, a thin layer can effectively insulate the ice sheet and inhibit any changes in air temperature from affecting the ice temperature. This can be seen in Figure 5/7/.

Correlation of snow cover data with field conditions can be very difficult. In large open spaces such as frozen water bodies, snow will tend to blow across and be deposited around the edges. Also snow that falls on ice may cause subsidence of the ice which will result in flooding and freezing of the snow to form "snow ice". Therefore snow depth data from locations on land may not accurately describe the snow conditions on an ice sheet. An example of typical snow and ice conditions can be seen in Figure 6/5/.

A discussion of attempts made to correlate meteorological snow data to reported field measurements is also given in the section describing the estimation of thrusts at Ontario dam sites.

2.2.5 Ice Thickness

The thrust developed by an ice sheet due to rising air temperatures is a function of the ice thickness for ice to approximately 30 centimetres thick. Above this thickness, it appears that the temperature change is not able to penetrate the ice sheet and develop high stress in the

lower area of the ice before those developed in the upper layer are diminished by creep of the ice. This phenomenon is shown in Figure 7/5/.

Differential ice thickness may also affect ice pressures. Pressure may be shed from thinner ice to thicker ice. In many cases, ice in reservoirs can be thin or non-existent in sections due to flowing water. This may cause ice pressures to be redistributed to other portions of the ice.

2.2.6 Reservoir Geometry

No real studies have been done on how the shape of the reservoir can affect the magnitude of the ice forces developed. There are, however, measured values that indicate that the magnitude of the forces developed are a function of the steepness of the slopes surrounding the reservoir. The steeper the shores, the greater the forces that develop.

In the winter of 1950-51, measurements were made at a number of reservoirs with a variety of shore conditions in the mountains of Colorado. Thrusts of 3.6 to 5.8 kips/ft were measured at Antero and Shadow Mountain, where the shores are relatively flat. The steeper shores of the Evergreen reservoir resulted in measurements of approximately 9.4 kips/ft. The steep, rocky shores of the Tarryall reservoir showed the highest forces with measured values of 17 kips/ft/2/.

As with other materials, the effect of confinement on the stress developed is an important feature. Biaxially restrained ice will be able to develop much greater stress than uniaxially restrained ice. This effect is confirmed by the values given above for the different ranges of shore steepness. Typically, an ice sheet is considered to be in a uniaxial stress state unless surrounded by near-vertical shores/3/.

The shape of the headpond area may also have an effect on the stresses that are applied to a dam. An irregularly-shaped perimeter would have "hardpoints" that would take a majority of the load, and little would actually reach the dam. This effect would be similar to arching effects that have been observed in soil and rock mechanics. Quantification of the effects of headpond perimeter shape would be quite difficult.

2.2.7 Cracks

Cracks can have an effect on the magnitude of the ice thrusts developed since open cracks would absorb strain and reduce the overall stress in the ice sheet. Most ice sheets are cracked to a certain degree. Cracks form when the upper layer of the ice expands or contracts more rapidly than the lower layer due to differential temperature changes. This can cause the development of tensile forces which easily crack the ice. Infilling of cracks is common, however, so prediction of their existence in the ice sheet is difficult.

The effects of ice cracks on the pressures developed is as difficult as trying to predict the effect of discontinuities in other materials such as soil and rock. Laboratory testing of small

homogeneous samples will not be able to describe the field behaviour of a large ice sheet composed of discrete sections. Currently, cracking is ignored as it is too hard to quantify. This will generally lead to higher predicted thrusts when compared to those that will occur in the field.

2.2.8 Reservoir Level Fluctuations

Changes in reservoir level can cause an ice sheet to buckle at some point. If this failure point re-freezes and the water level changes again, then the horizontal thrust will increase due to arching of the ice sheet. The magnitude of the increase may be related to the weight of the ice sheet, its buoyancy, and the rate of reservoir level change.

The effects of reservoir level changes will vary from location to location as a function of dam operating procedures. Arching of ice sheets may cause significant horizontal thrusts but prediction of this phenomenon is difficult.

3.0 METHODS USED TO PREDICT ICE FORCES

Methods that have been proposed for the prediction of thermal ice forces have been based upon either measured values from field and laboratory studies or by numerical models. Numerical models that have been developed to predict the magnitude of thermal ice forces normally predict ice temperature changes by application of the one dimensional heat flow equation. Stresses in the ice sheet due to these temperature changes are then determined by the use of a rheological equation. Below is a discussion of some of these methods.

3.1 Monfore's Method

In the 1950's, Monfore recommended a design method based upon his laboratory work. This work consisted of controlling the temperature rise inside 4 inch diameter ice specimens and recording the pressure required to maintain the sample length. This testing resulted in a series of graphs of ice pressures developed due to changes in ice temperature. His prediction method consisted of matching the temperature change of the ice to the graphs, as shown in Figure 3/2/, to obtain the expected pressure.

Later work by Monfore showed that his method was able to predict the ice forces measured in the field. Field measurements of ice temperature changes and ice forces developed in the ice cover on a reservoir with little snow cover were compared to predicted ice force values. Table II/8/ lists some of the measured versus computed thrust values. From this table, it appears that there is good agreement between the values. The extent of this study, however, is so limited that the results are not conclusive.

These results have also faced criticism because of the variation in the correlations. Willmot/9/ questioned some of the procedures used by Monfore and pointed out that some

of the variations between other measured and calculated values were as great as 28 percent. Willmot argued that Monfore's correlation was purely coincidental.

Monfore gave no means by which to calculate ice temperatures based upon meteorologic data. His method has probably not been widely used because it requires measurements of ice temperature.

Until further research has been done, the validity of this prediction method is questionable.

3.2 Method of Drouin and Michel

Drouin and Michel have proposed a numerical method for ice thrust prediction as a function of meteorologic conditions. Below is a discussion of how the method of Drouin and Michel deals with problems of predicting temperature fluctuations within an ice sheet, and the stresses developed by these fluctuations. This method has faced criticism from several authors because of its uncharacteristic relationship between the rate of temperature rise and the magnitude of the pressures developed.

3.2.1 Temperature Distribution in an Ice Sheet

Drouin and Michel used the equation for one dimensional heat flow to the ice sheet. This equation was solved for three types of temperature rise: step, linear, and sinusoidal. The step or instantaneous rise was dismissed as it seldom occurred in nature. The two principal temperature change patterns considered were linear and sinusoidal rises.

During the solution of the heat flow equation for sinusoidal temperature rises, it has been suggested that Drouin and Michel made an error. They used the Fourier solution for a semi-infinite space undergoing cyclic temperature variations, however, they use the result of a single sinusoidal temperature rise from one constant temperature to another. This was considered to be an unacceptable solution and found to underestimate both the rate of temperature rise and the total temperature rise of the ice sheet as shown in Figure 8 /4/. This was one reason why they developed their unorthodox theory that maximum thrusts would be developed by long, slow temperature rises/4/.

Drouin and Michel have attempted to prove their theory of temperature variation within an ice sheet by comparing the measured and calculated temperatures at a 15 centimetre depth in an ice sheet. This is shown in Figure 9/5/. At this depth, however, the effects of solar radiation may not be as prominent and the differences are, therefore, small. Correlation between measured and calculated temperatures should have been done at several depths in the ice sheet in order to prove their theory.

In their method, Drouin and Michel also make the assumption that the surface temperature of the ice is equal to the air temperature. They support their assumption by stating that measurements made on an ice sheet for a whole winter only showed a negligible maximum difference of 1.7°C between the ice surface temperature and the air temperature.It has been

noted, however, that the surface temperature of the ice may be quite different from the air due to the influx of solar radiation and the radiation of heat from the ice sheet/4/. One author has even stated that he has observed ice emitting heat to the air on a cold, calm, sunny late afternoon/3/.

The validity of each of the arguments presented above is questionable, however, it appears that Drouin and Michel may have been too simplistic in their assumptions. This disagreement in methods also highlights the requirement for further, more thorough, field measurements.

3.2.2 Stress Prediction

The method presented by Drouin and Michel uses a rheological model for ice given by the equation/4/:

$$\frac{\delta \sigma}{\delta t} = \dot{\epsilon} E_s - 2b\beta E_s \left(\left(\frac{\eta_0}{\beta} + \epsilon t\right) - \frac{\sigma(t)}{E_s}\right)\left(\frac{\sigma(t)}{2p}\right)^m \qquad (3)$$

where σ is the stress, $\dot{\epsilon}$ is the strain rate, t is time, E_s is the apparent Young's modulus, η_0 is the number of dislocations (cracks), β is the rate of multiplication of dislocations, b is Burger's vector, and p and m are constants. This equation has been solved numerically and used to calculate thrust at discrete levels in an ice sheet due to sinusoidal air temperature rises of different durations. The ice temperature at the upper surface was assumed to be the same as the air temperature and the temperature distribution within the ice was assumed to be initially linear, being 0°C at the lower surface.

Figures 10 and 11/5/ show the results from numerical calculations using this method. The figures are for two different types of ice. Curves are shown for various starting air temperatures that increase to 0 °C over a given time period. These plots also show that the highest thermal thrusts are developed as a result of temperature increases over long time periods at lower rates. This is explained by the theory that the thermal "wave" is able to penetrate more deeply into the ice sheet before the upper surface reaches its yield point.

3.2.3 Discussion

The method proposed by Drouin and Michel was among the first of its kind presented in North America. At the time it appeared to be a logical model to describe ice behaviour, however, it has not been correlated with any field measurements of thermal ice forces. The assumptions made in the method have been criticized by several authors, however, for lack of a better, more easily applicable method; this method is often suggested for design purposes/3/.

The assumptions made by Drouin and Michel have been criticized primarily on their pressure-temperature relationship. Bergdahl and Wernersson say that the "weird"

dependence of pressure on the rate of temperature increase is likely due to an error in their thermal calculations. Drouin and Michel also neglect the thermal boundary layer that exists between the upper surface of an ice sheet and the air. Bergdahl and Wernersson state that this boundary layer is too important to ignore/4/.

The parameters used to describe ice behaviour have also been questioned because Drouin and Michel use a value of Young's modulus of about 1.5 GPa at -10°C, whereas measurements have indicated this value should be between 4 GPa and 6.8 GPa at -10 °C /4,10/. This discrepancy in values for Young's modulus is discussed in a later section of this report.

Overall, it has been suggested that the method of Drouin and Michel will give low thrust predictions especially when considering rapid temperature changes over short time periods. There are no known correlations between measured values and those predicted by the method of Drouin and Michel. Use of this method is not recommended as it will likely give low or erroneous values.

3.3 Method of Bergdahl and Wernersson

The method proposed by Bergdahl for the theoretical determination of thermal ice forces appears to be the most promising numerical method to date. In principal, the method is similar to the method proposed by Drouin and Michel in that the temperature difference is calculated by a heat flow equation and pressures are calculated using a rheological equation for ice. This method differs from that of Drouin and Michel in that the assumptions made concerning the initial ice temperature conditions are quite different and the rheological equation is much simpler.

3.3.1 Temperature Distribution in the Ice Sheet

The temperature distribution within the ice sheet for this method is also calculated using a variation of the one dimensional heat flow equation. This is given as/4/:

$$\frac{\delta\theta}{\delta t} = H^2 \frac{\delta^2\theta}{\delta x^2} + p(x,t) \qquad (4)$$

The term, p(x,t), is accounted for by determining the change in ice temperature using an "energy balance" method for different boundary conditions. A finite difference method was used to solve this equation and it did not have the same problems as the Fourier series estimation used by Drouin and Michel.

The energy balance method includes consideration of the flux of radiation to and from the ice sheet. The upper surface temperature of the ice is not set equal to the air temperature. This is done because "energy exchange between the ice cover and the atmosphere is too complex to allow the surface temperature to be set equal to the air temperature"/4/. The

energy balance method includes consideration of energy flux of five types (+ increases ice temperature, - decreases ice temperature): net solar radiation (+)(irradiation-reflection), long-wave radiation from the atmosphere (+), emitted long-wave radiation from ice (-), sensible heat transfer because of different temperatures of air and ice surface (+ or -), and heat transfer due to vapour from air condensing on ice (+) or sublimation of ice to vapour (-)/4/.

These energy sources are quantified by considering the atmospheric conditions such as air temperature, wind speed, cloudiness, relative humidity, and barometric pressure. The specific boundary conditions related to the effects of each of these factors on the temperature of the upper and lower surfaces of the ice sheet, and at internal points in the ice sheet are not described here but can be found in Bergdahl and Wernersson.

Examples of some calculated versus measured temperature conditions are shown in Figures 12 and 13/4/. These figures show that agreement is quite good between the measured and calculated temperatures for the entire thickness of the ice sheet. It is important to note, however, that these figures are lacking in measurements near the upper surface.

3.3.2 Stress Prediction

The rheological model for the calculation of ice pressure proposed by Bergdahl and Wernersson is quite simple. Graphically it can be described as being composed of a linear spring and a non-linear dashpot. The linear spring is used to describe the elastic behaviour of the ice which is determined by the Young's modulus of the ice, which is a function of the ice temperature. The non-linear dashpot is used to describe the creep behaviour of the ice and is based upon variables that are functions of the ice temperature and the strain rate. This relationship is described by the equation/4/:

$$\dot{\epsilon} = \frac{1}{E}\sigma + KD\sigma^{n} \qquad (5)$$

where $\dot{\epsilon}$ is the strain rate, E is the Young's modulus, σ is the stress, D is a function of temperature, and K and n are functions of strain rate and temperature. Solution of this equation can be done numerically, graphically or analytically to determine pressures along discrete layers within the ice sheet. It has been found that pressure calculations need not be done too accurately and layers of about 5 cm thick are adequate/4/.

There are no published figures or tables for the effects of various atmospheric conditions on the development of ice pressures as the variables controlling temperature change are numerous. Some examples of pressures calculated using this model versus those determined in the laboratory are given in Figures 14 and 15/4/. These figures show that this model generally overestimates the ice pressures but provides a possible upper bound.

3.3.4 Discussion

The energy balance method used to determine ice temperature variation and the rheological model for ice proposed in this method appear to be logical. The model however seems to predict high stresses.

A comparison of the method of Bergdahl and Wernersson with field measurements was done by Cox/10/. Cox found that the theoretical method overestimated the compressive and tensile stresses in the ice. By modifying the parameters used in the theoretical method, Cox was able to obtain much better agreement between the measured and predicted values. This is seen in Figure 16/10/. Like many other published reports, Cox's study is lacking in meteorologic data that could be used by others to verify ice thrust predictions.

There is still concern, however, whether the measured values of the thermal ice thrusts were accurate. While the measured and predicted values showed reasonably good agreement, Cox cautioned that considerably more work would have to be done before thermal ice thrusts can be predicted with confidence. Cox also suggested that part of the problem was due to uncertainty of the mechanical properties of ice. He also concluded that further work should be done to determine the mechanical properties of columnar ice at higher temperatures and lower strain rates. Establishment of a data base of measured stress and strain data for a range of temperature variations and ice thicknesses was also considered to be an important objective in order to verify existing and future models. Since this is the only comparison between this method and the measured values, the correlation may simply be a coincidence. Further field evaluation would be necessary before the model could be considered to be accurate.

Results from this method have also compared favourably to the results of laboratory tests on biaxially restrained ice sheets conducted by Lindgren. This comparison is seen in Figure 17/4/.

Overall it has been suggested that this method will give high estimates for ice thrusts.

4.0 PREDICTION OF THRUST ON DAMS IN NORTHERN ONTARIO

Three areas: Sudbury, North Bay, and Muskoka were chosen as locations at which attempts were to be made to predict the magnitude of thermal ice forces. The methods chosen were those of Drouin and Michel and Bergdahl and Wernersson as these were expected to give lower and upper bounds, respectively, for ice forces. In order to make these predictions, Table III/3/ was used for the method of Drouin and Michel and Figure 18/7/ was used for the method of Bergdahl and Wernersson.

An attempt was also made to correlate some of the weather data and these predicted values to field measurements made by Willmot.

4.1 Assumptions

To use Table III and Figure 18, certain assumptions had to be made. These include:

a) The ice was completely free of snow cover. This is the worst possible condition and should result in high thrust values being predicted.

b) The method of Bergdahl and Wernersson was assumed to give results similar to the tests conducted by Lindgren. This similarity was shown previously in Figure 17. This assumption was made so that Figure 18 could be used and to avoid having to develop a computer program for the method of Bergdahl and Wernersson. No tables like the one used for the method of Drouin and Michel exist for the method of Bergdahl and Wernersson. Figure 18 was taken from Lindgren, but extrapolated for use here; the extrapolations may not be valid for the entire range of temperature changes.

c) The ice temperature at the upper surface of the ice was assumed to be equal to the air temperature and they both rose at the same rate. These are the conditions recommended for the use of Table III /3/. When using the method of Bergdahl and Wernersson, this assumption should yield values of thrust that are greater than if the true relationship between air temperature and ice temperature were used. Measurements by Willmot as seen in Figure 19/11/ show that there is a time lag between air and ice temperature changes. This figure also shows that the ice temperature change is not as great as the air temperature change.

d) The effects of solar radiation were ignored.

e) Uniaxial stress conditions were assumed. This corresponds to flat or gently sloping reservoir shores. Results from Lindgren's graph are converted from biaxial to uniaxial by the relationship $\sigma_{uniaxial} = \sigma_{biaxial}/1.85$. This relationship was recommended by Michel/1/.

f) Maximum temperature changes over 5-, 10-, and 20-hour periods, after complete freeze-over and before the first deterioration of ice, were used for the analysis.

g) Complete freeze-over and break-up dates were taken from published records/12/, which give these dates for water bodies throughout Canada.

h) There were no cracks in the ice.

These assumptions were necessary to simplify the analysis. The effects of these assumptions on the thrust values predicted is uncertain. The values obtained are not meant to be exact values, but only bounds of expected ice thrusts. Comments found in Bergdahl and Wernersson indicated that the values predicted will likely be higher than those that will occur in the field. The method of Drouin and Michel is expected to give lower values than those that will occur in the field due to their peculiar temperature rise-pressure relationship.

Generally it may be stated that the method of Bergdahl and Wernersson will predict high values, whereas the method of Drouin and Michel will predict low values.

4.2 Analysis

From this analysis, the estimated maximum ice thrusts for each year from approximately 1952 to 1989 were calculated using hourly temperature data from the Sudbury, North Bay, and Muskoka airports. This was done by looking at the yearly maximum temperature rise over 5-, 10-, and 20-hour periods. This maximum temperature rise was then used to predict the maximum expected thermal ice thrust. The temperature changes and calculated ice thrusts are given in Appendix A. The results of this analysis are summarized in Tables 4 to 6. These results seem to indicate that thrusts of 10 kips/linear foot or greater are occurring annually.

Attempts were also made to match the temperature changes measured by Willmot to those found in the weather records. The temperature changes measured by Willmot at the Otto Holden Dam that caused the pressures measured on Feb 12, 1957, were great. The air temperature rose from a starting temperature of about -24°C to -4.4°C over 6 hours, a rise of approximately 3.3°C/hour. A value of more than 18 kips/ linear foot was observed to be a function of these conditions and arch action due to lowering of the reservoir. The combination of these conditions is shown in Figures 19 and 20/11/. Temperature changes from this starting temperature and of this magnitude and duration were not found to exist in the weather data for any of the three regions. A search of weather data from North Bay, approximately 30 miles (48 km) west of Otto Holden Dam, showed temperature changes to be much less severe even for this specific date. This may be seen in Figure 21. The inability to match temperatures across this short distance indicates a possible microclimate at the dam site.

Snow cover data on this date was also analyzed and measurements from North Bay indicated that there was 28 centimetres on the ground, 7 centimetres of which had just fallen on February 9, 1957. This is seen in Figure 22. These values indicate that the ice would appear to have been well insulated from these temperature changes. This indicates the difficulty in extrapolating snow cover data to other regions as there may have been no snow at the dam or "snow ice" could have formed. The snow conditions at the dam on February 12, 1957, were not reported, however, the ice sheet 5 feet from the dam face was described as being "1 in. (2.5 cm) ice, 8 in. (10 cm) of air and ice needles, 1 in. (2.5 cm) of ice, 4 in. (10 cm) of air and ice needles, and then solid ice" on February 15, 1957/11/. This type of layering indicates that the snow had caused the ice to be flooded and "snow ice" had formed. This 14 inches (35 cm) of ice, air, and ice needles roughly corresponds to the 28 centimetres of snow, but the difference is also large enough to indicate that this type of correlation might be pretentious. Also measurements of ice thickness 30 and 200 feet (9 to 61 m) from the dam face were given as 12-16 inches (30 to 40 cm) and there was no mention of snow cover at these two points.

Attempts were also made to match other snow cover data to values reported by Willmot for Des Joachims and Otto Holden GS. The description of the ice sheet was not as detailed for these cases as they were for the February 12, 1957, incident at Otto Holden GS. For all of the cases listed by Willmot, he reported no snow cover. Meteorologic records indicate significant snow cover depths. A comparison of these values can be seen on Table VII/8/. Again, it is difficult to predict whether this snow had turned to "snow ice", or was not even deposited at the site.

Figure 18/7/ of Lindgren's results indicate a thrust of approximately 38 kips/ linear foot for the temperature change shown in Figure 19/11/. The table for the method of Drouin and Michel predicts a thrust of 12 kips/ linear foot. These two predicted values appear to form upper and lower limits for the approximately 20 kips/linear foot measured by Willmot. This is only one case, however, and such a broad conclusion is tenuous.

4.3 Discussion

The method of Drouin and Michel tends to predict lower values than those from the method of Bergdahl and Wernersson. This could be due in part to the fact that Drouin and Michel assume a lower Young's modulus for the ice. The greatest difference occurs when rapid temperature changes take place over short periods of time. This is likely due to the possible error that Drouin and Michel made when solving the heat flow equation. Over longer time periods, the two methods predict values that agree more closely. The values predicted by the method of Bergdahl and Wernersson are likely excessively high because of the assumption that ice temperature fluctuations parallel air temperature changes.

Therefore, it appears that the two methods give quite different thrust values and exhibit quite different behaviour over short, rapid temperature changes. Rapid temperature changes are quite common due to solar radiation which results in diurnal warming and cooling trends. This difference points out the need for further research into the thermal fluctuations within an ice sheet and their effect on pressure development. The assumptions that had to be made in order to do this simplified analysis also appear to have exaggerated the differences between the thrust values estimated by the two methods.

Correlation of the two prediction methods with measured data reported by Willmot was inconclusive. The two methods appear to form upper and lower bounds on the ice pressures, however, the lack of data makes this conclusion pretentious.

Snow and temperature data from the meteorologic records is very difficult to correlate to field conditions, and again, the field data is scarce. Snow is easily altered to "snow ice" and will have little insulating effect on the ice sheet. Even the temperature change that caused the high thrust value measured at the Otto Holden dam on February 12, 1957, could not be matched to temperature records from North Bay. The approximately 8 centimetres of snow that fell at North Bay on February 9, 1957 is not mentioned as being at the Otto Holden dam site on February 12, 1957.

The method of Drouin and Michel, which is considered to give low ice thrust predictions, gave annual values for thrust that were at or above the standard design value of 10 kips/linear foot. Therefore, it appears that the potential conditions for the development of large ice thrusts exist annually.

5.0 ICE PROPERTIES

The models for ice behaviour discussed above appear unable to predict ice forces with confidence. This may be partially due to simplifications in the models, but is also due to a lack of understanding of ice properties. Like other numerical models, ice models are only as good as the parameters they use. The engineering properties and behaviour of ice are dependent on the crystal structure and temperature of the ice. Understanding how these factors affect the engineering properties is important for any study of ice forces. Below is a description of some of the properties of ice that make it a unique engineering material.

5.1 Crystal Structure

Ice in nature is composed of hexagonal crystals in a tetrahedral arrangement. This arrangement gives ice crystals a distinct elongated shape defined by a long "c" axis and a basal plane perpendicular to the "c" axis. The orientation of the "c" axis is very important to the behaviour of the ice as sliding on the basal plane is a common failure mechanism/8/.

5.2 Ice Growth

Ice development on lakes and rivers takes place in a direction perpendicular to the water surface. This is the direction of heat flow out of the water and ice forms in columnar structures parallel to this direction. The texture of the ice is dependent upon the rate of initial freezing. "Snow" ice is a random arrangement of the hexagonal ice crystals developed by the melting and freezing of snow cover on the ice.

These different ice structures exhibit different engineering properties. It is therefore, important to be sure of the type of ice and the effects that crystal orientation may have on the ice properties. Testing of ice properties should be done in a direction parallel to the direction of horizontal thrust development. This direction is commonly perpendicular to the "c" axis of the ice crystals. Recording the orientation of loading of experimental specimens with respect to their orientation in nature is an important part of any testing procedure.

5.3 ICE PROPERTIES

The strength of ice is both temperature and time dependent and is also a function of the orientation of the ice crystals with respect to the loading direction. Loading in nature will commonly occur perpendicular to the "c" axis, so this is the direction for which strength properties are normally determined. Figures 23 to 25/13/ show the crushing, tensile, and torsional strength of ice under various temperature conditions and loading orientations with respect to the "c" axis of the ice.

Figure 23/13/ shows that the crushing strength of ice perpendicular to the "c" axis is less than strength parallel to the "c" axis. This is likely due to sliding failure occurring along the basal planes. Since loading in nature will commonly occur perpendicular to the "c" axis, the crushing strength of ice should be taken as 400 to 800 psi (2.7 to 5.5 MPa) for temperatures ranging from 20°F to -40°F (-7°C to -40°C) respectively for loading perpendicular to the "c" axis.

The tensile strength behaviour of the ice is similar to that of the crushing strength. From Figure 24/13/, it is evident that the tensile strength varies from 200 psi (1.3 MPa) at 20°F (-7°C) to 350 psi (2.4 MPa) at -60°F (-51°C) for loading perpendicular to the "c" axis.

The torsional strength relationship is different from those above, but is still related to the crystal orientation and failure due to sliding along the basal plane. Torsional strength varies from 200 psi (1.3 MPa) at 20°F (-7°C) to 350 psi (2.4 MPa) at -40 °F (-40 °C) for loading perpendicular to the "c" axis as seen in Figure 25/13/.

5.4 Elastic Properties

During rapid loading and unloading, ice exhibits elastic behaviour which can be defined by the elastic parameters Young's modulus (E) and Poisson's ratio (v). Both of these values are dependent on the temperature of the ice. It is, therefore, important to consider this when using these values.

For loading perpendicular to the "c" axis, E has been measured to be from 0.8×10^6 psi (5.5 GPa) at 32°F (0°C) to 1.2×10^6 psi (8.3 GPa) at -40°F (-40°C). Poisson's ratio varies from 0.53 at 32 °F to approximately 0.37 at -40 °F. These relationships are shown in Figure 26/13/ and were determined by stressing at a rate of 5 psi/second/13/.

The values in this figure roughly correspond to the equation/4/:

$$E = (1-(0.012)(\theta))6.1 \text{ GPa} \qquad (6)$$

given by Bergdahl and Wernersson where θ is the ice temperature. This equation was found to lead to high values for Young's modulus as reported by Cox. For example, at -10°C, equation 4 gives E = 6.8 GPa, whereas Cox found that this value should be somewhere closer to 4 GPa/10/. Further testing would be necessary to determine which value is most accurate.

Young's modulus also exhibits variation with rate of loading. This, however, is limited to about 5% and is, therefore, neglected for most cases.

5.5 Plastic Properties

There are no specific properties defining the plastic behaviour of ice. Laboratory tests have shown that plastic behaviour of ice can affect the magnitude of the maximum pressure that may develop.

As an ice sheet initially begins expanding, pressure development is quite rapid. With time, the temperature increase in the upper section of the ice sheet causes it to behave in a plastic manner. Therefore, the pressure developed by a thermally expanding ice sheet reaches a threshold as the plastic deformation exceeds the strain developed due to thermal expansion. This effect was shown in Figure 2/2/.

Prediction of the maximum pressures developed before plastic behaviour causes a reduction in thrust is difficult. It illustrates the fact that the pressures developed in an ice sheet are not necessarily a function of the crushing strength of the ice. In fact, they may be much lower due to this plastic behaviour. The type of failure taking place will be a function of the rate of air temperature fluctuations and their effect on the temperature distribution within the ice sheet.

6.0 CONCLUSIONS

Few failures of dams due to thermal ice forces have been reported/1,2/. However, measurements and some reported failures of structures and back calculations of the forces required to cause failures indicate that very large thermal ice forces can develop. Vital information such as meteorologic data and ice conditions are lacking for the majority of the measurements and reported failures. Many other measured values have shown ice forces to be below the standard design value of 10 kips/linear foot.

There is a lack of rationale behind the standard design value of 10 kips/linear foot. Field measurements have shown that values greater than this can occur. A more rational design approach is necessary. A possible basis for this approach would be an analysis of meteorologic conditions over a certain return period and an estimation of the maximum possible thrust that could be developed under these conditions.

There have been several attempts made to try to measure or estimate the horizontal thrusts on dams by the thermal expansion of ice sheets. While most of them agree that the prediction involves two steps: determining temperature changes within the ice, and calculating the stresses due to the temperature changes, none of them have been able to model either of these steps with suitable confidence.

Controversy exists as to what assumptions may be made. Some models have been able to approximate measured values, however, these correlations are limited. The lack of available field data to correlate these models and proper understanding of ice properties has compounded these problems.

The method of Bergdahl and Wernersson appears to be promising, based on the results of Cox. The confidence with which this model can be used, however, is limited because of the lack of other correlations between predicted and measured values.

The weather records for the areas in Ontario described in this report indicate that temperature conditions that will likely cause thermal ice thrust greater than 10 kips/ linear foot across the dam face occur annually. Many simplifying assumptions had to be made in order to estimate the thermal ice thrusts reported in this paper, therefore, the validity of the reported values is questionable. Also microclimate effects seem to cause the temperatures measured at the dam sites to be different from those temperatures recorded at local airports. This makes ice thrust predictions from weather records a dubious practice unless meteorologic conditions are measured at the dam site.

One of the major assumptions for these estimates was that there was no snow cover on the ice, as this would be the worst possible condition. Examination of snow cover data from meteorologic records indicated that most of the areas involved in the study had a significant amount of snow cover for the majority of the winter. Comparison of recorded snow cover data with field conditions failed to show a relationship between the two. Snow cover can cause subsidence and flooding of ice and the formation of "snow ice".

Water level changes in the reservoir can cause arching of the ice sheet and further increase horizontal thrusts/9/. This factor has not been included in the analysis but must also be considered.

As it stands, there is no way to reliably and confidently estimate the thermal ice forces that a dam will be subjected to over its lifetime. There is too much variation in measured and predicted values. For the areas of study, there is no indication that the design value of 10 kips/ linear foot can be lowered. Conversely there is no firm indication that this value need be increased. Until some of the problems associated with the prediction of ice thrusts can be resolved and until further field measurements have been taken, there is no indication that the design value is too high or too low.

7.0 RECOMMENDATIONS

Further field work is necessary to develop a data base of ice sheet behaviour over a range of conditions. These measurements will be needed to confirm the accuracy of any models developed. The existing field measurements are often lacking in important details such as measured ice temperature or climatic conditions.

A comprehensive field study would involve coincidental monitoring of the thrusts developed in an ice sheet, temperature distributions within the ice, and atmospheric conditions. Recording of all of these values would allow for correlation between each of these factors and assist in the verification of existing models or help to develop new ones.

Laboratory testing of some type should also be done in order to develop a better understanding of ice properties and behaviour over a wider range of conditions. This may lead to a more suitable rheological equation for ice and yield values for use in any models of ice.

If no new models are to be developed, then future research should focus on attempts to verify existing models by comparison with field values, as was done by Cox. The method of Bergdahl and Wernersson, with the modifications made by Cox, would appear to be the "best" model investigated.

From the work done for this report, it has been found that rough approximations may be made by applying temperature change data to the chart published by Lindgren, reducing it to uniaxial conditions, and then taking half of this value. This was the approximate correlation between Willmot's measured value at Otto Holden GS on Feb. 12, 1957, and Lindgren's chart. This is only a rough correlation and is not recommended as a design method. The methods of Drouin and Michel, and Bergdahl and Wernersson, may give bounds for expected ice pressures.

If no further work is done in the field of thermal ice pressure estimation, then it should be accepted that ice pressures may exceed 10 kips/linear foot. Therefore, some sort of remedial measures might be necessary to reduce the ice pressure acting on hydraulic structures.

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REFERENCES

1. Gerard, R. 1989. Thermal ice loads on dams and ancillary structures: a brief review. In Proceedings of Dam Safety Seminar, Edmonton, Alberta, September 1989. pp. 123-137.

2. Michel, B. 1970. Ice Pressure on Engineering Structures, CRREL Report, Hanover, New Hampshire.

3. Wortley, C.A. 1985. Great Lakes Small-Craft Harbour and Structure Design for Ice Conditions: An Engineering Manual, University of Wisconsin Sea Grant Institute. Report WIS-SG-84-426.

4. Bergdahl, L. 1978. Thermal Ice Pressure in Lake Covers, Report Series A:2, Dept. of Hydraulics, Chalmers University of Technology, Goteburg, Sweden.

5. Michel, B. 1978. Ice Mechanics, Les Presses de L'Université Laval, Quebec.

6. Bergdahl, L. and Wernersson, L. 1977. Calculated and Expected Thermal Ice Pressures in Five Swedish Lakes, Report Series A:2, Dept. of Hydraulics, Chalmers University of Technology, Goteburg, Sweden.

7. Lindgren, S. 1970. Thermal ice pressure. In Proceedings IAHR Ice Symposium, Reykjavik Iceland pp. 6.7:1-40.

8. Aita, D. 1987. Ice pressure on dams. Undergraduate Thesis, University of Toronto, Division of Geo-Engineering, Toronto, Ontario.

9. Willmot, J.G. 1956. Investigation of ice pressure on dams: general progress report 1951-56. Ontario Hydro Research Division, Report No. 56-522.

10. Cox, G.F.N. 1984. A preliminary investigation of thermal ice pressures. Cold Regions Science and Technology, 9:221-229.

11. Willmot, J.G. 1957. Investigation of ice pressure on dams: ice pressure at Otto Holden G.S. on February 12th 1957. Ontario Hydro Research Division, Report No. 57-253.

12. Allen, W.T.R. 1977. Freeze-up, Break-up and Ice Thicknesses in Canada., Fisheries and Environment Canada, Atmospheric Environment Service.

13. Gold, L.W. 1968. The ice pressure problem. In Conference Proceedings from Ice Seminar, Calgary, Alberta, CIM Special Volume 10, 1969, pp. 27-30.

TABLE I/3/

THERMAL PROPERTIES OF ICE AT VARIOUS TEMPERATURES

Thermal Properties of Ice (after Drouin and Michel 1974)

Temperature (°F)	Thermal Expansion (1/°F)	Specific Heat (Btu/lb./°F)	Thermal Conductivity (Btu in./hr./ft.^{2}/°F)
32	0.000030	0.506	15.6
14	0.000029	0.487	16.1
- 4	0.000028	0.468	16.8
-22	0.000027	0.450	17.6
-40	0.000026	0.431	18.6

TABLE II /3/

CORRELATIONS BETWEEN MEASURED AND PREDICTED THRUSTS

	Maximum Thrust From Figures (kips/lin. ft.)	Maximum Thrust Measured by Gages (kips/lin. ft.)
Jan. 14	6	6
Jan. 21	13	12
Jan. 22	11	14

TABLE III/3/

THERMAL ICE PRESSURES DEVELOPED IN AN ICE SHEET RESTRAINED IN ONE DIRECTION

Approximate Thickness of Ice		Ice Surface Temperature					
		-10 C (14 F)		-20 C (-4 F)		-30 C (-22 F)	
(cm)	(in.)	S1 Ice	T1 Ice	S1 Ice	T1 Ice	S1 Ice	T1 Ice
		Duration of Temperature Increase: 5 Hours					
51	20	*5	4	11	8	19	13
76	30	5	4	11	8	20	14
102	40	5	4	11	8	20	15
		Duration of Temperature Increase: 10 Hours					
51	20	6	5	14	11	23	16
76	30	7	5	15	11	24	18
102	40	7	5	15	12	25	19
		Duration of Temperature Increase: 20 Hours					
51	20	9	7	18	13	27	18
76	30	9	8	20	15	30	20
102	40	9	8	20	16	32	22

* Pressure of thermal origin in kips/linear foot due to temperature rise from initial ice surface temperature to zero Celcius over given time period.

TABLE IV

CALCULATED THERMAL ICE PRESSURES;
RESULTS OF ANALYSIS USING WEATHER DATA FROM NORTH BAY

North Bay				
Time Period (hours)	Initial Temp. (deg. C)	Method Used*	Average (kips/ft)	Std. Deviation (kips/ft)
5	< -10	D&M	7.2	1.1
5	< -10	L	32.1	4.7
5	< -20	D&M	7.3	0.9
5	< -20	L	34.3	3.4
5	< -30	D&M	6.5	1.8
5	< -30	L	37.1	2.5
10	< -10	D&M	12	1.6
10	< -10	L	29	5
10	< -20	D&M	12.4	1.3
10	< -20	L	31	3.6
10	< -30	D&M	10	2.9
10	< -30	L	33	2.8
20	< -10	D&M	17.5	3.3
20	< -10	L	26	4.7
20	< -20	D&M	17	3.4
20	< -20	L	27	3.5
20	< -30	D&M	11	5.7
20	< -30	L	29	4

* methods used were Drouin and Michel (D&M) and Lindgren (L).

TABLE V

CALCULATED THERMAL ICE PRESSURES;
RESULTS OF ANALYSIS USING WEATHER DATA FROM SUDBURY

Sudbury				
Time Period (hours)	Initial Temp. (deg. C)	Method Used*	Average (kips/ft)	Std. Deviation (kips/ft)
5	< -10	D&M	7.7	1.2
5	< -10	L	32.3	4.7
5	< -20	D&M	7.9	1.3
5	< -20	L	34.2	3.2
5	< -30	D&M	7.3	1.9
5	< -30	L	38.4	2.3
10	< -10	D&M	12.2	2.8
10	< -10	L	27.8	5.8
10	< -20	D&M	13	1.9
10	< -20	L	29.6	4.9
10	< -30	D&M	10.8	3.4
10	< -30	L	34.4	2.7
20	< -10	D&M	18	3.4
20	< -10	L	27	4.5
20	< -20	D&M	17.9	3.5
20	< -20	L	27.4	4.1
20	< -30	D&M	12.7	5.4
20	< -30	L	29.5	3.8

* methods used were Drouin and Michel (D&M) and Lindgren (L).

TABLE VI

CALCULATED THERMAL ICE PRESSURES;
RESULTS OF ANALYSIS USING WEATHER DATA FROM MUSKOKA

Muskoka				
Time Period (hours)	Initial Temp. (deg. C)	Method Used*	Average (kips/ft)	Std. Deviation (kips/ft)
5	< -10	D&M	11.5	1.9
5	< -10	L	39.7	4.3
5	< -20	D&M	11.8	1.8
5	< -20	L	40.7	3.7
5	< -30	D&M	12.2	2
5	< -30	L	42.5	1.5
10	< -10	D&M	16.7	2.3
10	< -10	L	36.1	4.2
10	< -20	D&M	17	2
10	< -20	L	36.5	3.8
10	< -30	D&M	16.6	2.6
10	< -30	L	38.9	1.6
20	< -10	D&M	18.2	2.8
20	< -10	L	28.3	4.2
20	< -20	D&M	18.3	2.5
20	< -20	L	28.8	3.5
20	< -30	D&M	17.1	3.1
20	< -30	L	32.2	1.5

* methods used were Drouin and Michel (D&M) and Lindgren (L).

TABLE VII from /8/ (modified)

MAXIMUM SEASONAL ICE PRESSURES DUE TO THERMAL EXPANSION
MEASURED BY WILLMOT (1956) WITH SNOW COVER DATA
FROM WEATHER RECORDS INCLUDED

Location	Season	Date	Ice Thickness (cm)	Snow Cover (cm)			Rise in Air Temp. (deg. F)	Meas. Thrust (lbs/lin ft)
				Willmot	North Bay	Sudbury		
Des Joachims	1951-2	28/12/51	20.3	-	*n/a	n/a	22	4,900
	2-3	11/3/53	38	-	n/a	n/a	38	6,000
	3-4	23/2/54	25-36	-	n/a	n/a	20	5,400
	4-5	5-6/2/55	-	-	56	n/a	29	7,300
	5-6	1/1/56	-	-	38	52	28	3,900
Otto Holden G.S.	1951-2	-	-	-	n/a	n/a	-	Not Meas.
	2-3	-	Approx. zero	-	n/a	n/a	-	-
	3-4	13/2/54	30-40	15-20	n/a	n/a	27	3,000
	4-5	-	-	-	n/a	n/a	-	Approx. zero
	5-6	28/2/56	-	-	69	71	29	2,800
Pine Portage G.S.	1951-2	-	-	-	n/a	n/a	-	Not Meas.
	2-3	8/1/53	< 15	-	n/a	n/a	35	4,000
	3-4	30/12/53	20-25	-	n/a	n/a	21	3,100
	4-5	31/1/55	-	9	n/a	n/a	40	5,000
	5-6	-	-	-	n/a	n/a	-	Approx. zero

*n/a indicates snow data not found in records

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184236-RD

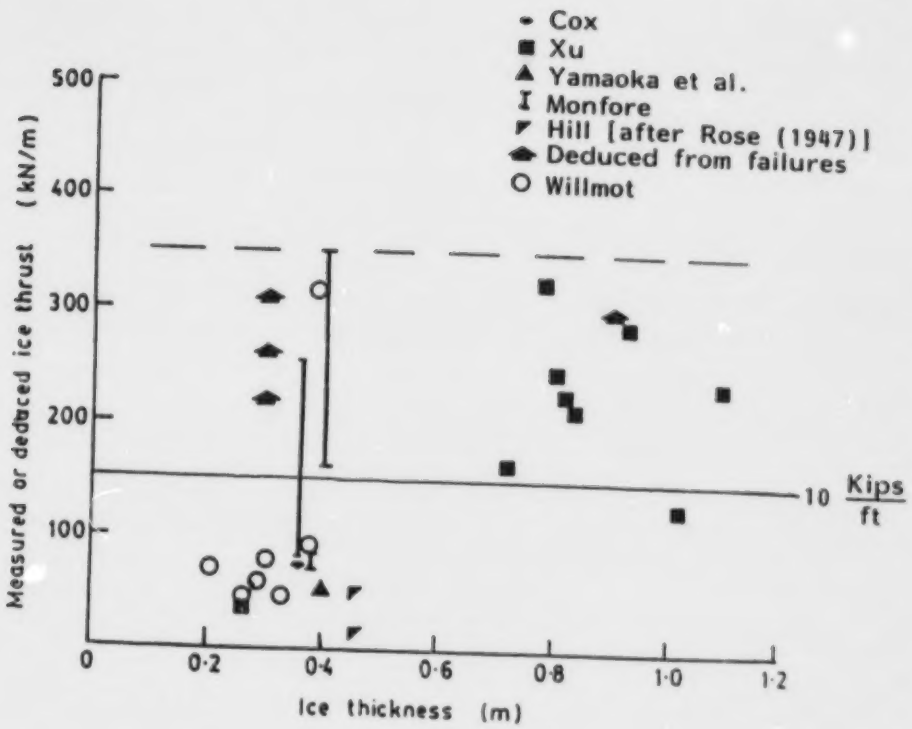


FIGURE 1/1/
FIELD MEASUREMENTS OF THERMAL ICE THRUST
(1kN/m ≃ 0.06853 kip/ft)

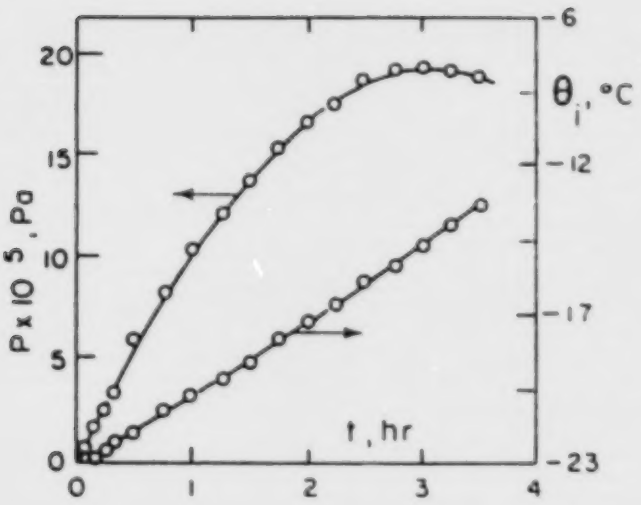
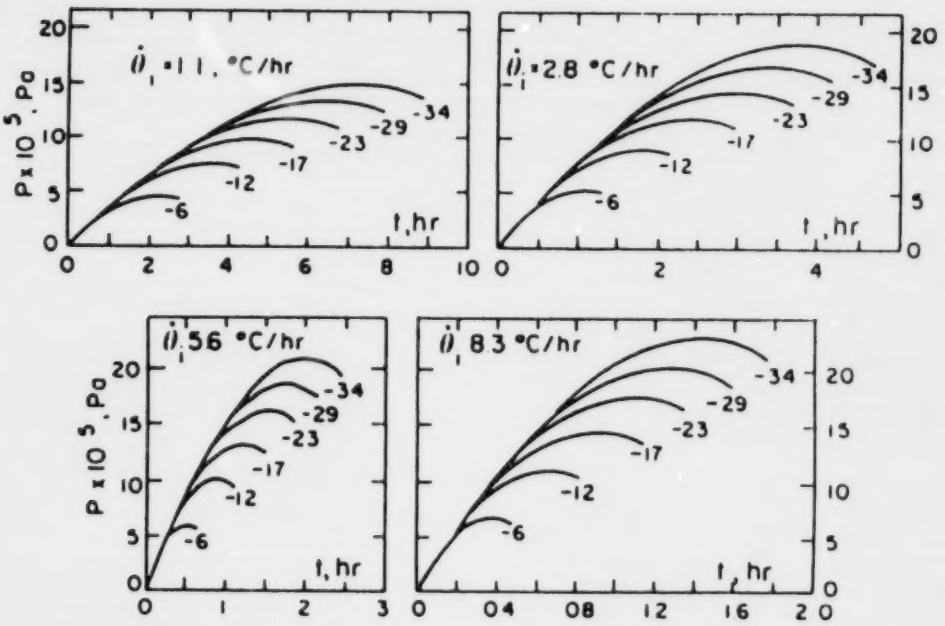


FIGURE 2 /2/

TIME DEPENDENT STRESS-STRAIN BEHAVIOUR OF ICE
(1 kPa ≃ 0.021 kip/ft for 12" (30cm) thick ice)
(1 kPa ≃ 0.031 kip/ft for 16" (40cm) thick ice)



Average pressure-time curves for a temperature rise of 2°, 5°, 10° and 15°F/hr (1.1°, 2.8°, 5.6° and 8.3°C/hr) from indicated initial temperatures.

FIGURE 3 /2/

RESULTS FROM MONFORE'S LABORATORY TESTING
(1 kPa ≃ 0.021 kip/ft for 12" (30cm) thick ice)
(1 kPa ≃ 0.031 kip/ft for 16" (40cm) thick ice)

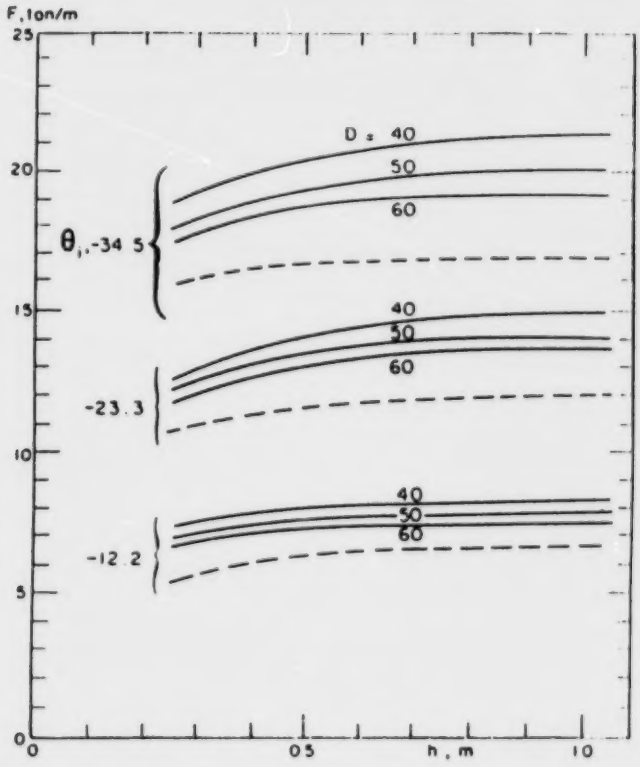
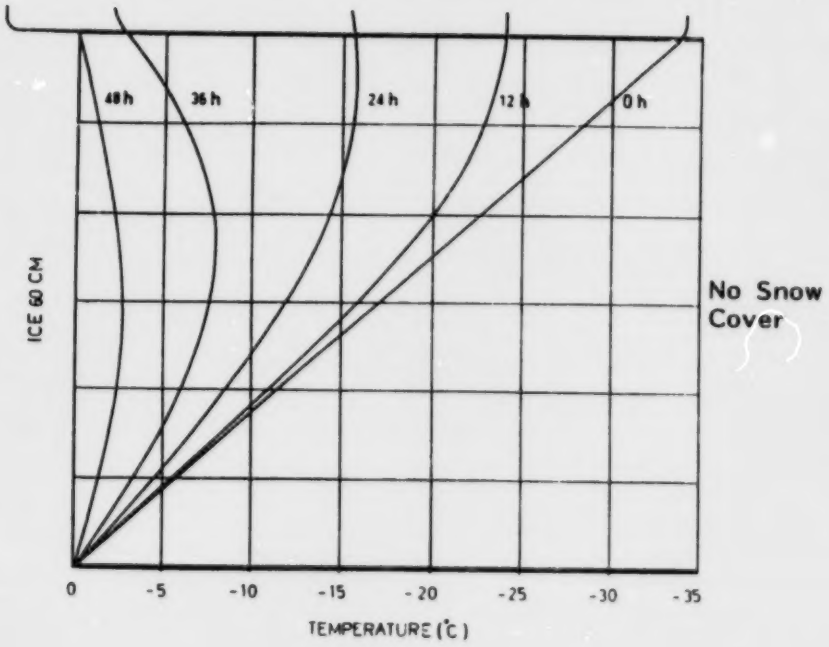


FIGURE 4 /5/

EFFECT OF SOLAR RADIATION ON ICE THRUST DEVELOPMENT AT THREE DIFFERENT LATITUDES FOR THREE INITIAL AIR TEMPERATURES
(1 ton/m = 0.672 kip/ft)



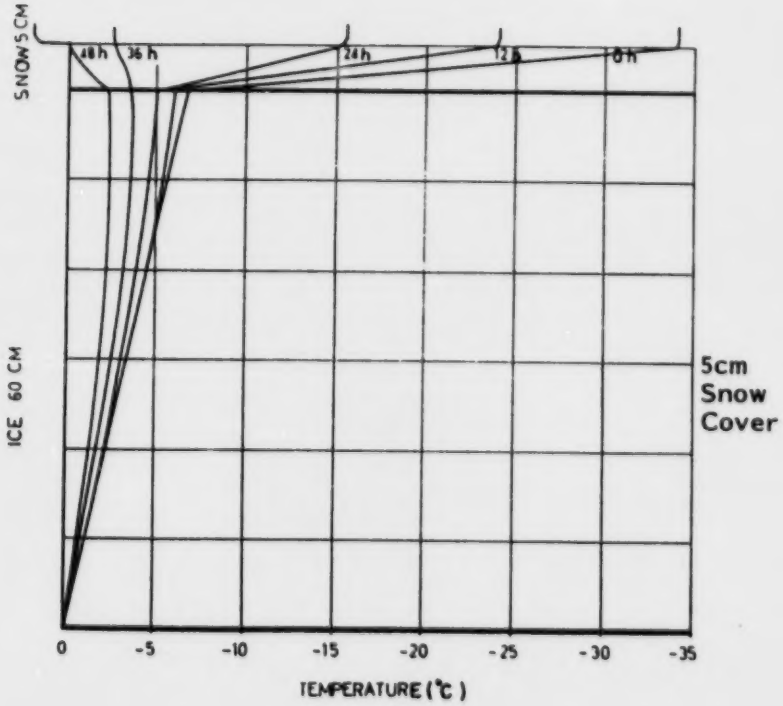


FIGURE 5 /7/

EFFECT OF SNOW COVER ON ICE TEMPERATURE CHANGE

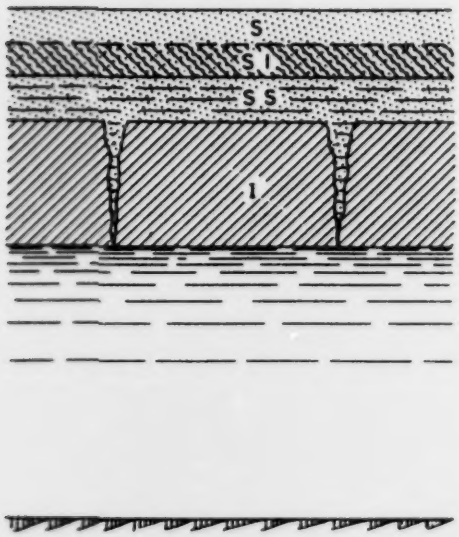


FIGURE 6 /5/

LAYERING EFFECT OF SNOW;
FRACTURED BLACK ICE (I) IS COVERED BY SNOW
SLUSH (SS), SNOW ICE (SI) AND SNOW (S)

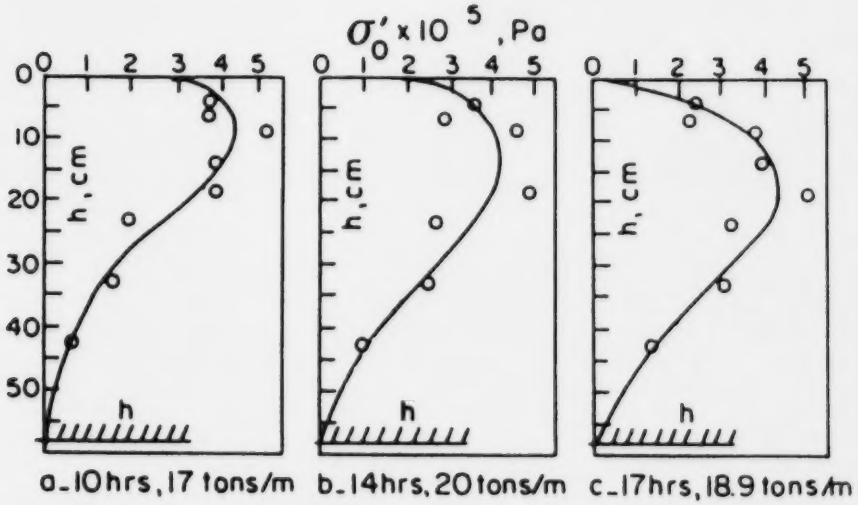
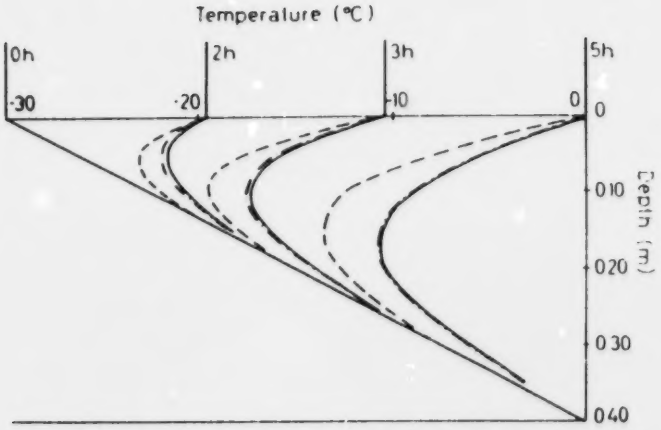


FIGURE 7 /5/

MEASURED PRESSURES IN ICE SHEET SHOWING CREEP BEHAVIOUR WITH TIME
(1 kPa ≃ 0.031 kip/ft for 16" (40cm) thick ice)
(1 ton/m ≃ 0.672 kip/ft)



Temperature profiles calculated in three different ways for the same boundary condition, ice surface temperatures equal to air temperature. Continuous line: Fourier series solution. Dash-dot line: Schmidt scheme. Dashed line: Drouin and Michel's expression $a = 1.15 - 10^{-6}$ m^2/s

FIGURE 8 /4/

ICE SHEET TEMPERATURE PREDICTION
BY METHOD OF DROUIN AND MICHEL
VERSUS TWO OTHER METHODS

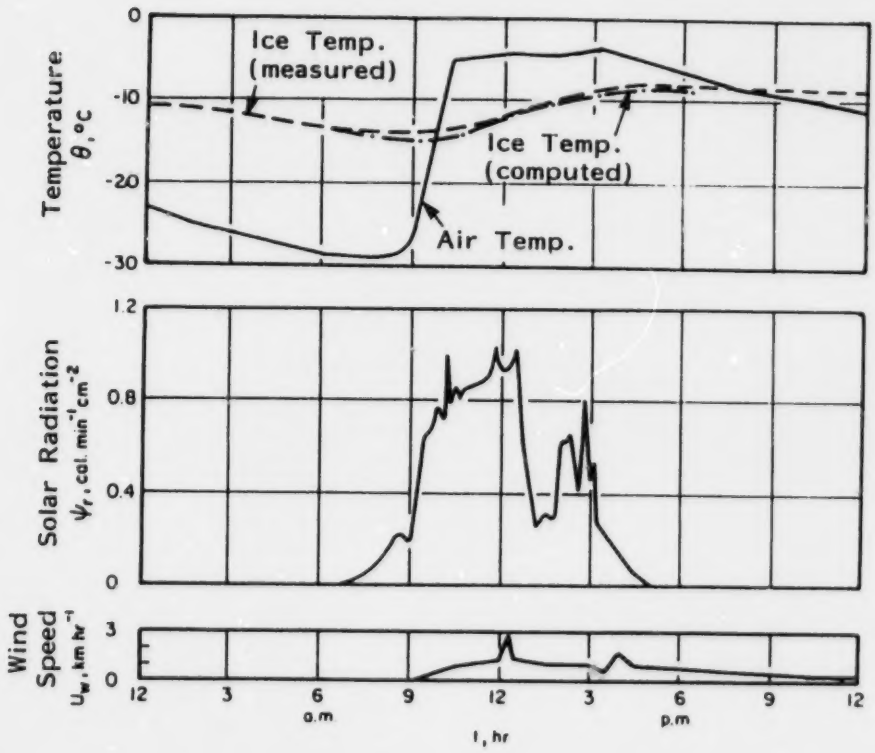


FIGURE 9 /5/

TEMPERATURES MEASURED VERSUS THOSE PREDICTED BY THE METHOD OF DROUIN AND MICHEL AT A 6" DEPTH IN ICE SHEET

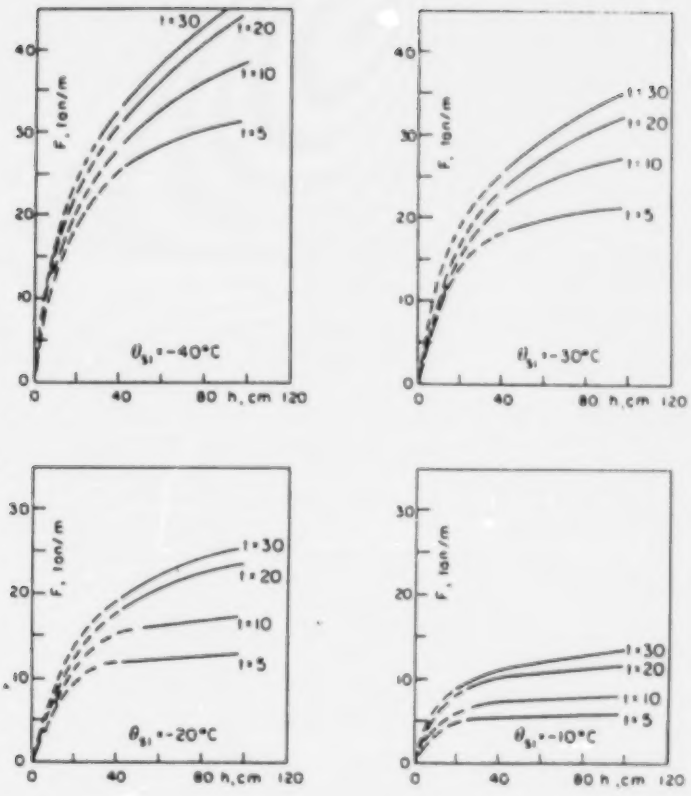


FIGURE 10 /5/

METHOD OF DROUIN AND MICHEL FOR T_1
ICE SHOWING MAXIMUM THRUST DEVELOPED FOR
SINUSOIDAL TEMPERATURE RISE OF DURATION t
(IN HOURS) FOR VARIOUS STARTING
TEMPERATURES (θ_{si}) AND ICE THICKNESSES (h)
(1 ton/m $\simeq$ 0.672 kip/ft)

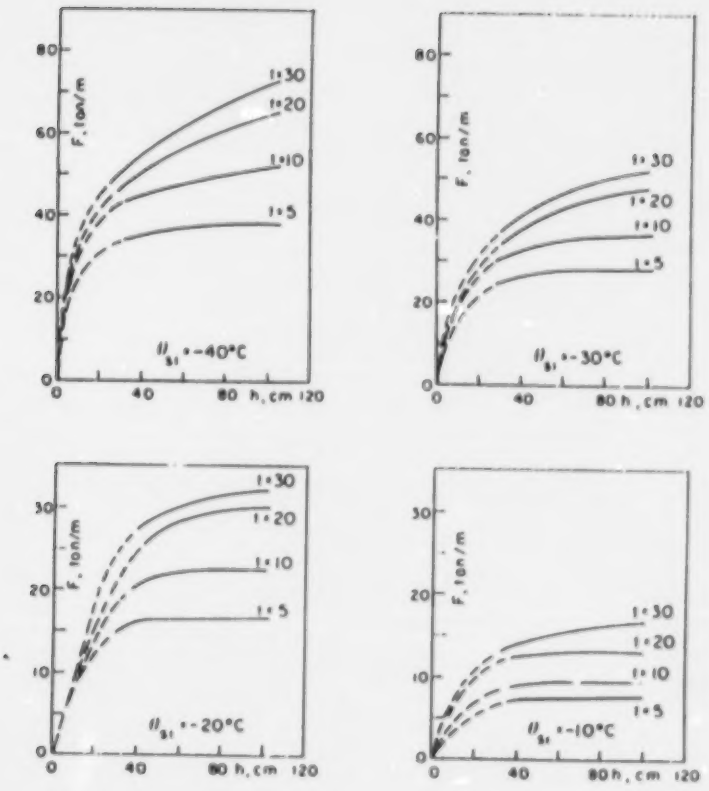


FIGURE 11 /5/

METHOD OF DROUIN AND MICHEL FOR S_1 ICE SHOWING MAXIMUM THRUST DEVELOPED FOR SINUSOIDAL TEMPERATURE RISE OF DURATION t (IN HOURS) FOR VARIOUS STARTING TEMPERATURES (θ_{si}) AND ICE THICKNESSES (h)
(1 ton/m ≃ 0.672 kip/ft)

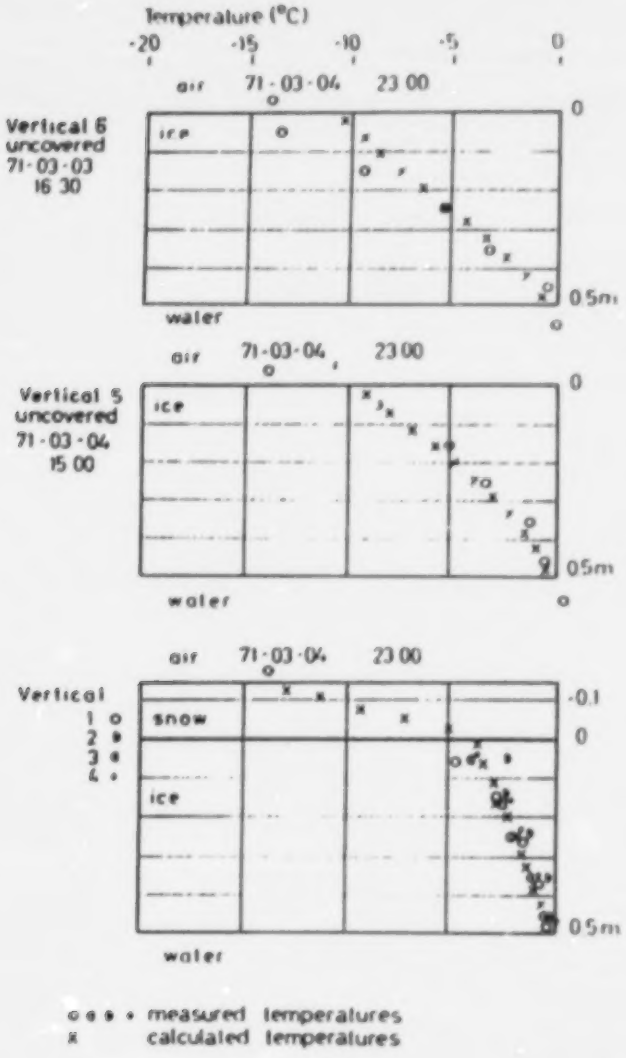


FIGURE 12 /4/

MEASURED VERSUS CALCULATED TEMPERATURES
IN ICE SHEET USING METHOD OF BERGDAHL AND WERNERSSON

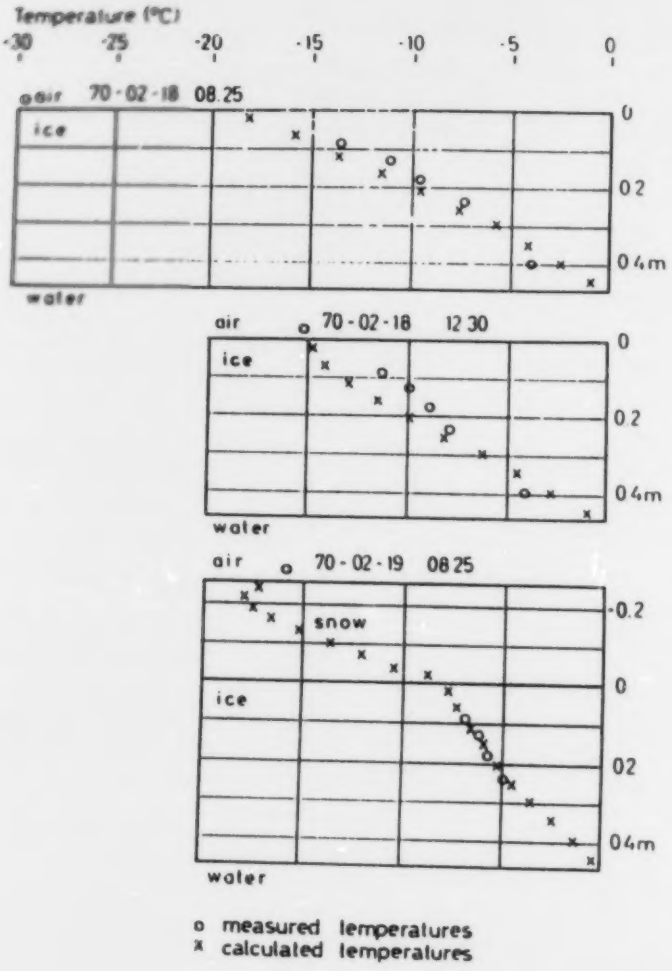
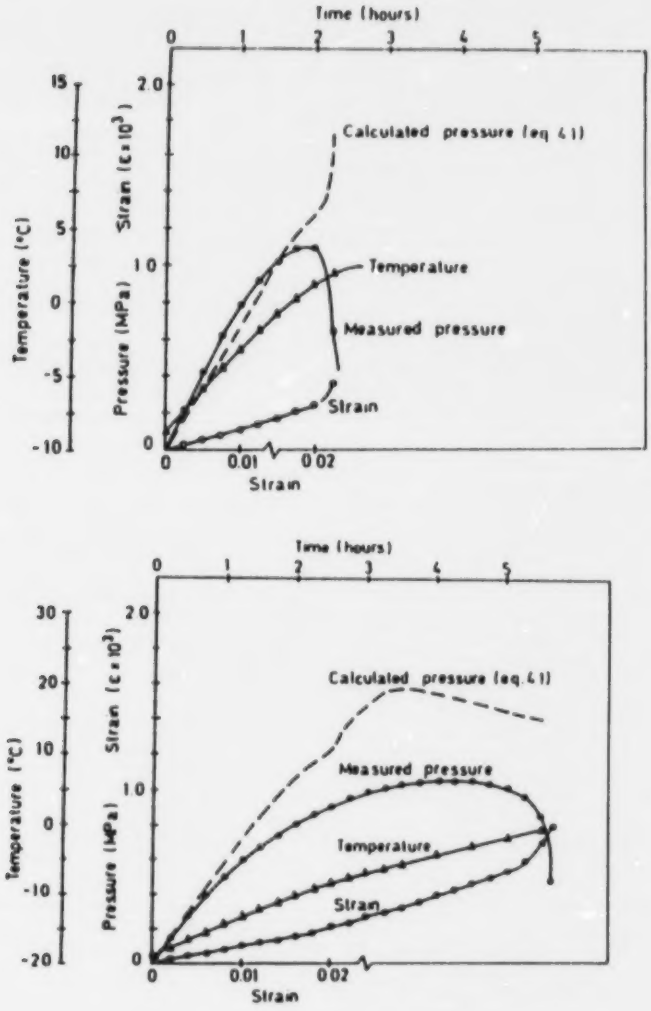


FIGURE 13 /4/

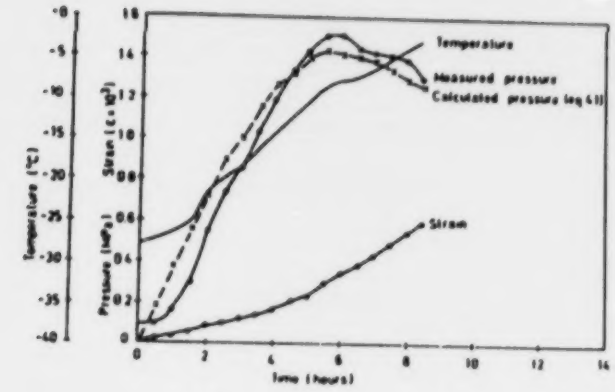
MEASURED ICE TEMPERATURES VERSUS THOSE CALCULATED BY THE METHOD OF BERGDAHL AND WERNERSSON

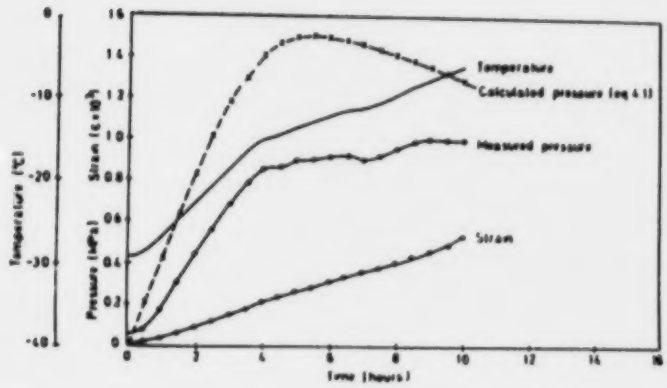


Comparison between measured ice pressure and ice pressure calculated on basis of Equation (4.1) and shown deformations. Experimental curves from Drouin and Michel (1971).

FIGURE 14 /4/

METHOD OF BERGDAHL AND WERNERSSON (EQUATION 4.1) VERSUS LABORATORY TEST RESULTS

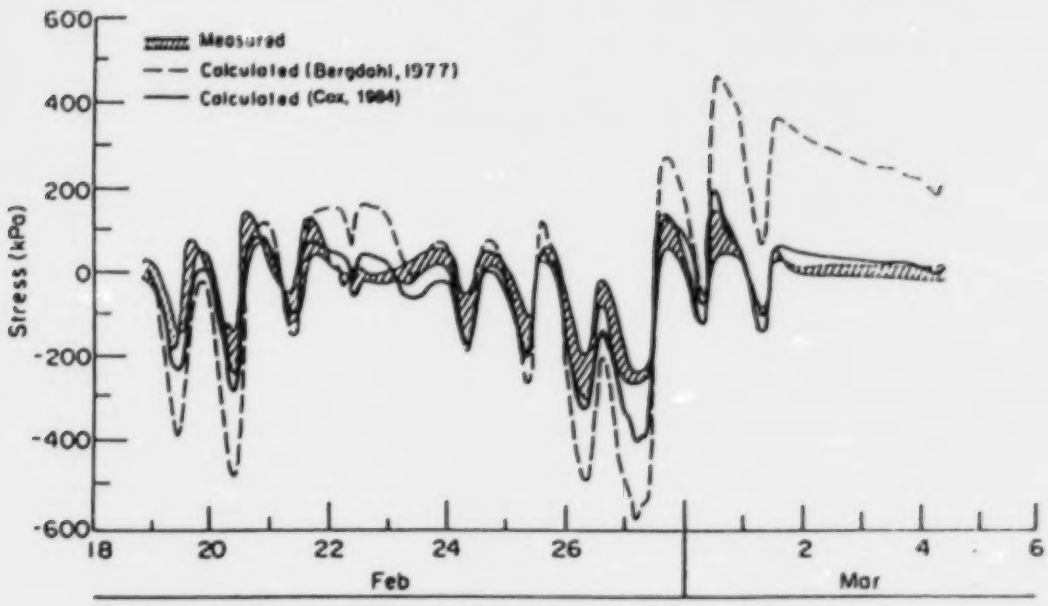




Comparison between measured ice pressure and ice pressure calculated on basis of Equation (4.1) and shown deformations. Experimental curves from Lindgren (1968).

FIGURE 15 /4/

METHOD OF BERGDAHL AND WERNERSSON (EQUATION 4.1) VERSUS LABORATORY TEST RESULTS



Measured (Gauge 514) versus calculated ice stresses.

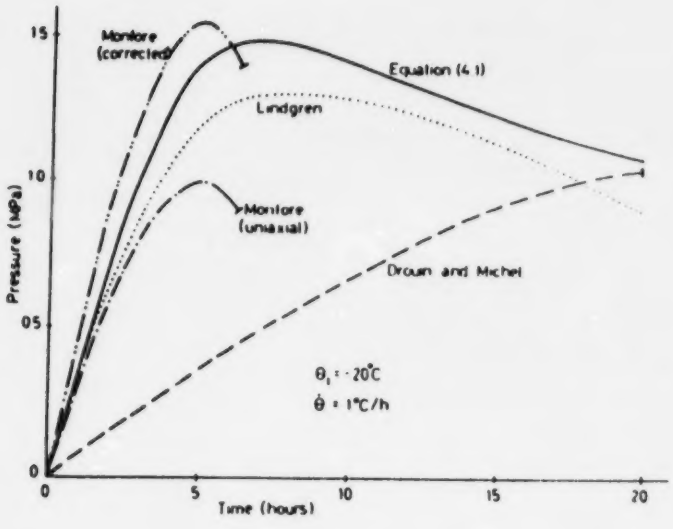
FIGURE 16 /10/

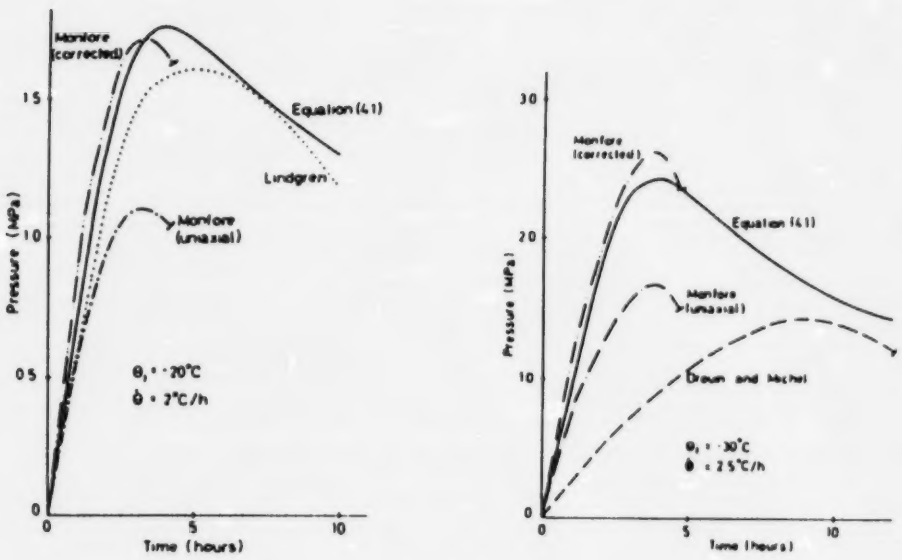
MEASURED VERSUS CALCULATED ICE THRUSTS

1 kPa ≃ 0.145 psi

1 kPa ≃ 0.021 kip/ft for 12" (30cm) thick ice

1 kPa ≃ 0.031 kip/ft for 16" (40cm) thick ice





Stress as a function of time for constant rates of change of temperature θ. Final temperature $0^{\circ}C$.

FIGURE 17 /4/

COMPARISON OF OTHER PREDICTION METHODS WITH THAT OF BERGDAHL AND WERNERSSON (EQUATION 4.1)

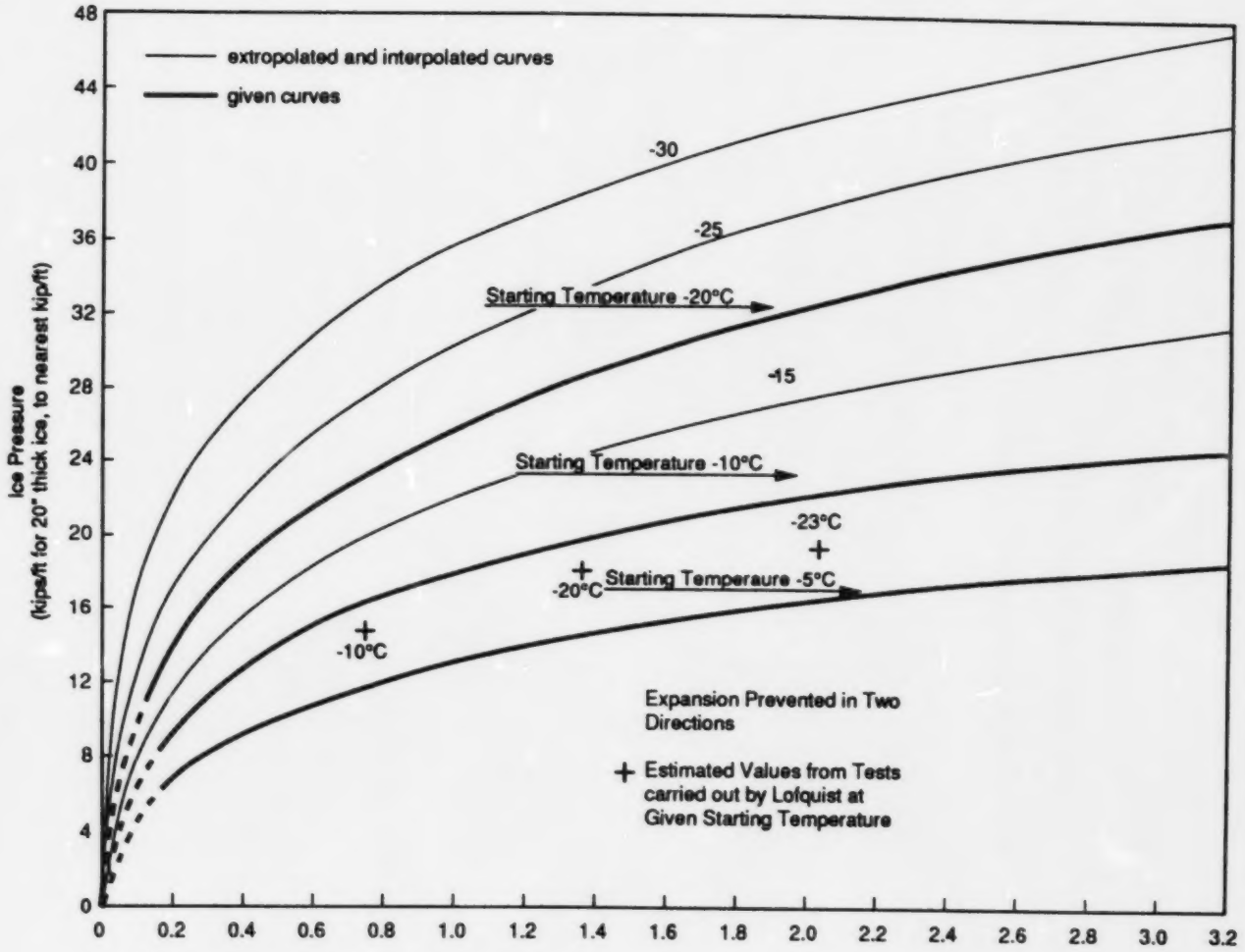


FIGURE 18 /7/

RATE OF TEMPERATURE RISE (°C/H)

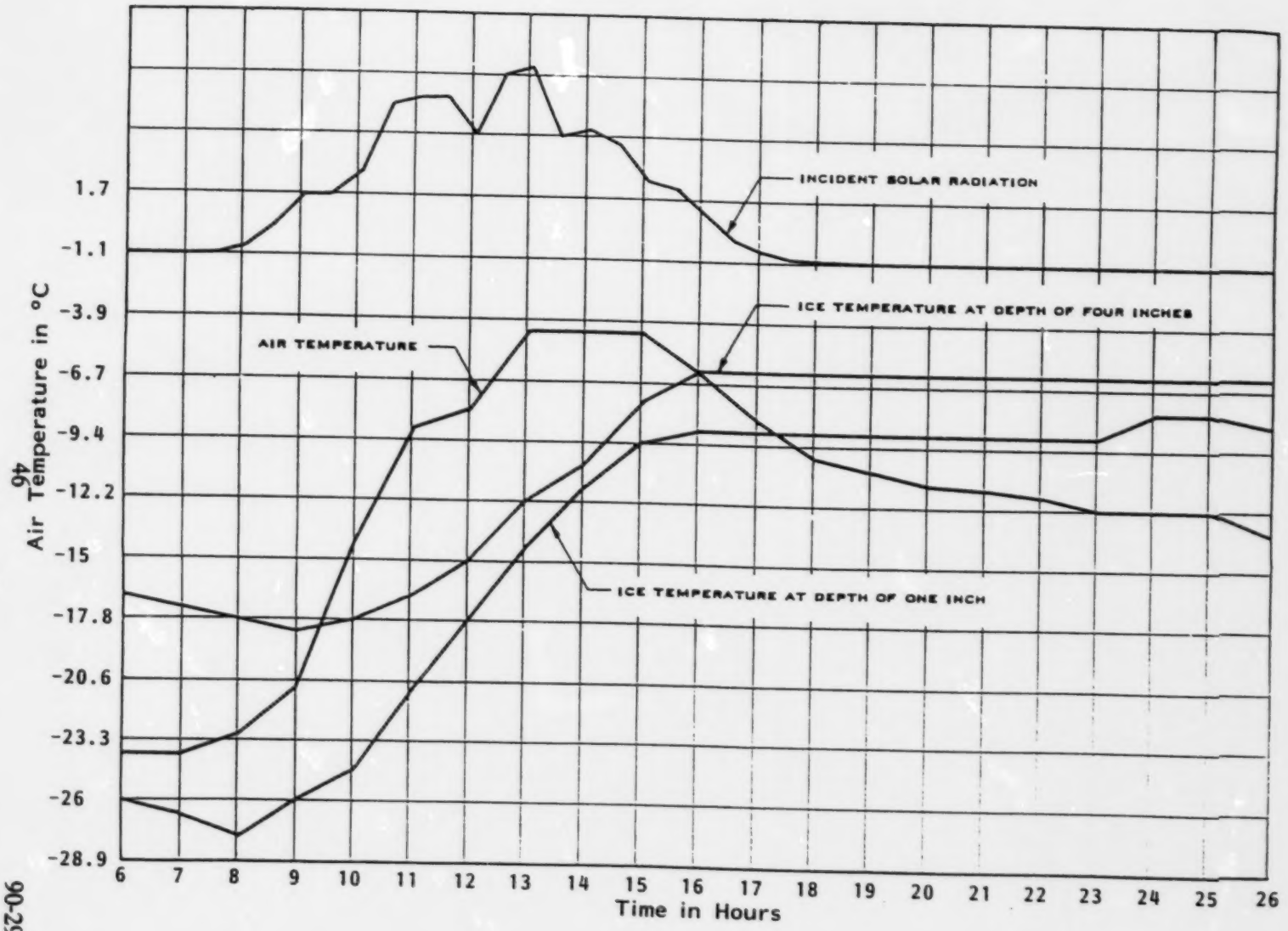


FIGURE 19 /11/

AIR AND ICE TEMPERATURES AND INCIDENT SOLAR RADIATION
AT OTTO HOLDEN G.S. ON FEBRUARY 12TH AND 13TH, 1957

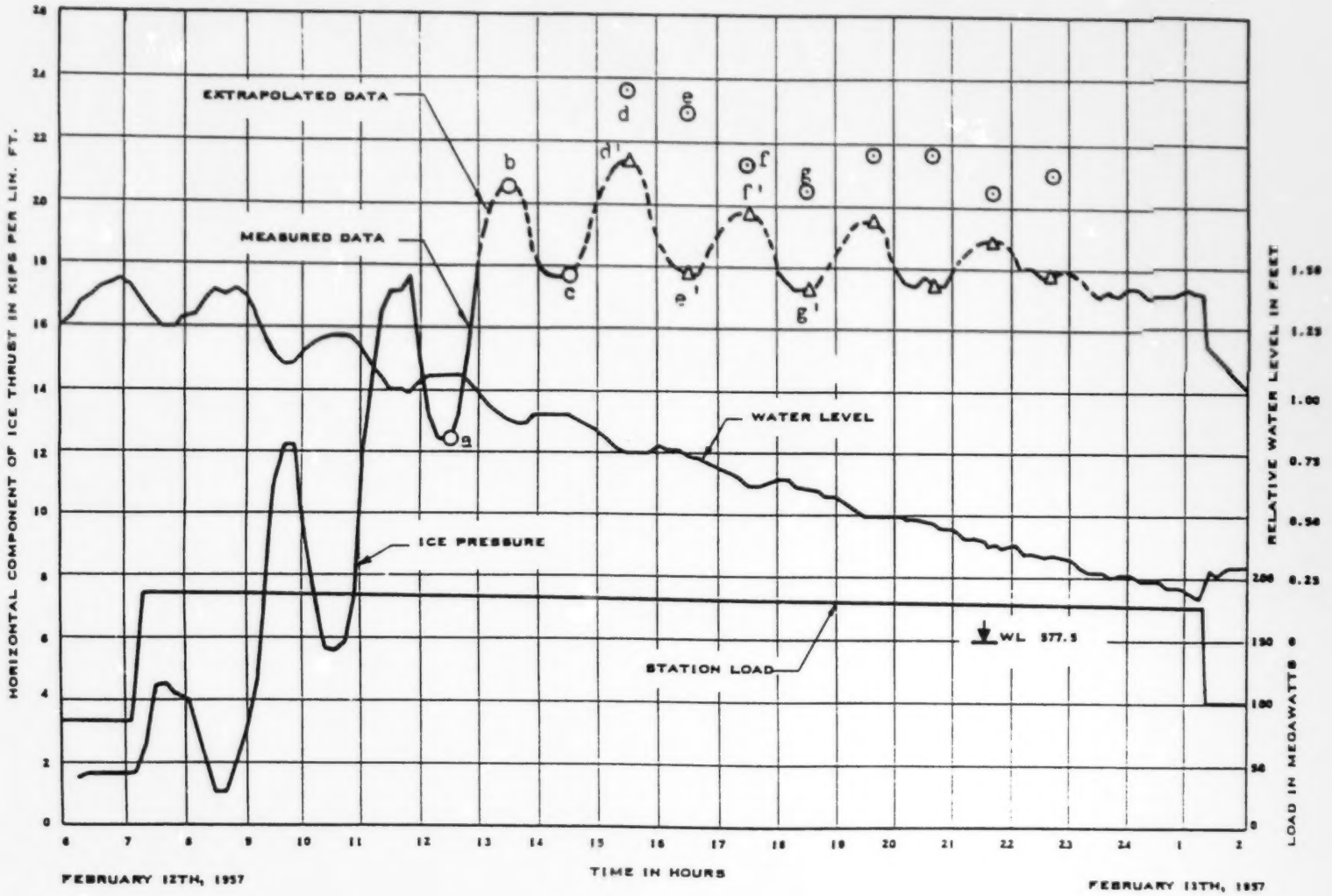


FIGURE 20 /11/

CURVES ON ICE PRESSURE FOREBAY ELEVATION AND STATION GENERATING LOAD VS TIME AT OTTO HOLDEN G.S. FROM 06:00 HOURS FEBRUARY 12TH TO 02:00 HOURS FEBRUARY 13TH 1957

90-293
184226-RD

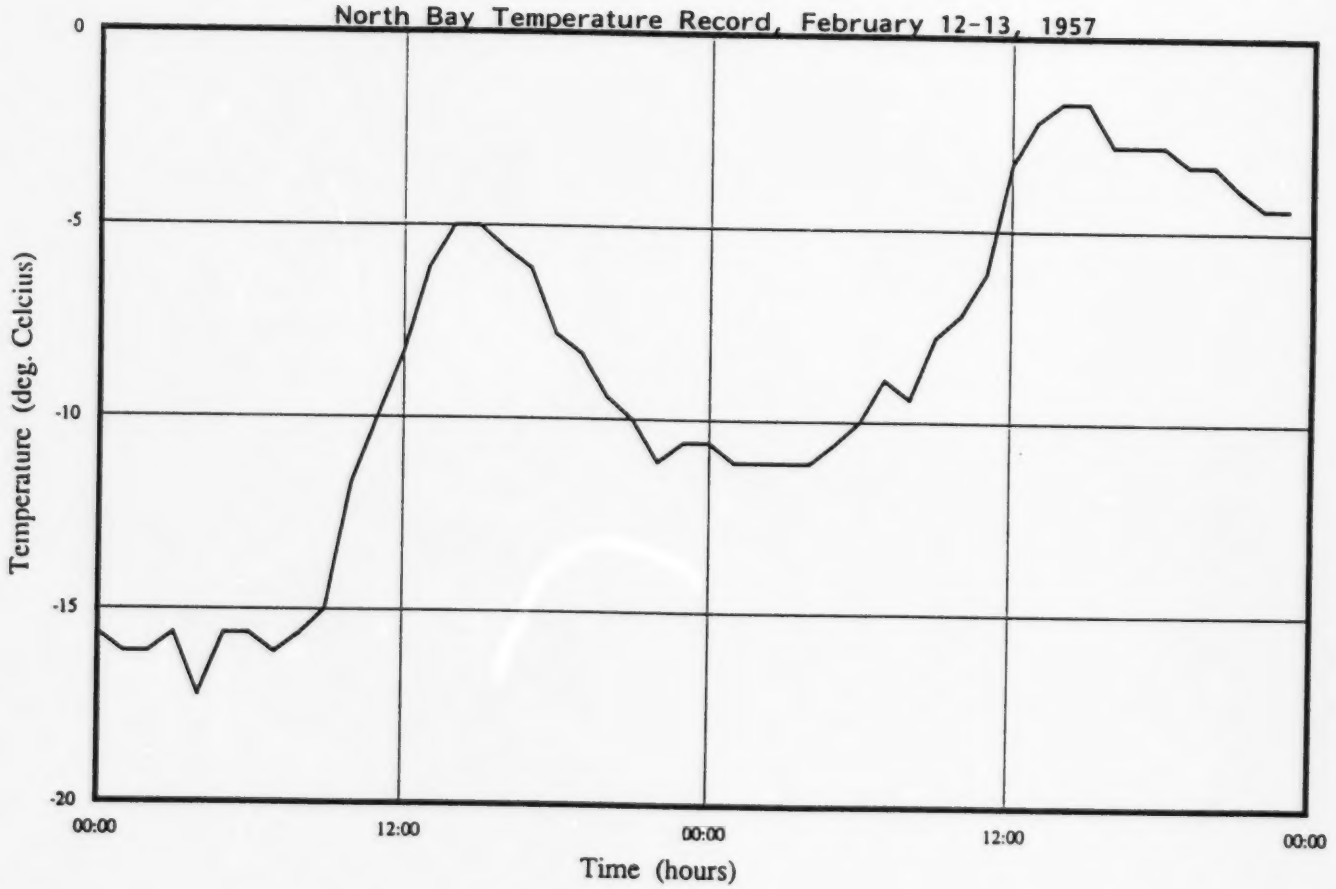


FIGURE 21

TEMPERATURES RECORDED AT NORTH BAY AIRPORT ON FEBRUARY 12-13, 1957

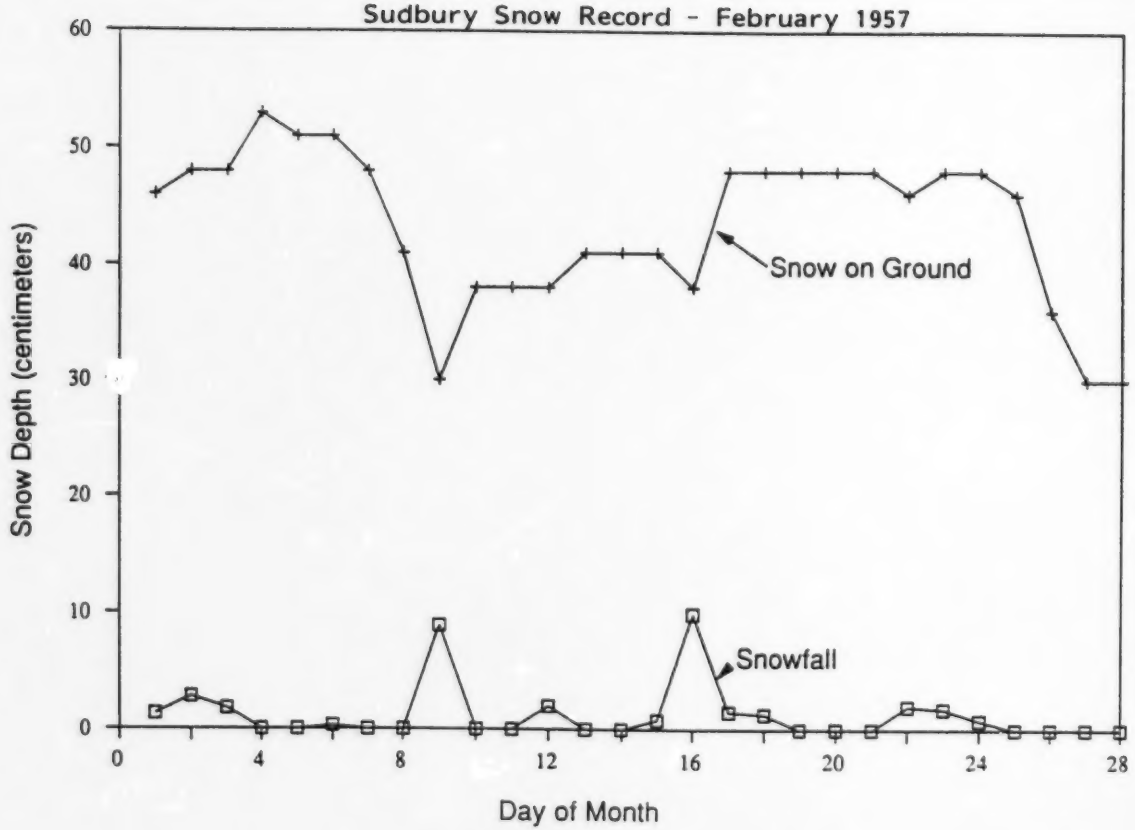


FIGURE 22

SNOW COVER AND SNOWFALL DATA RECORDED AT NORTH BAY AIRPORT FOR FEBRUARY 1957

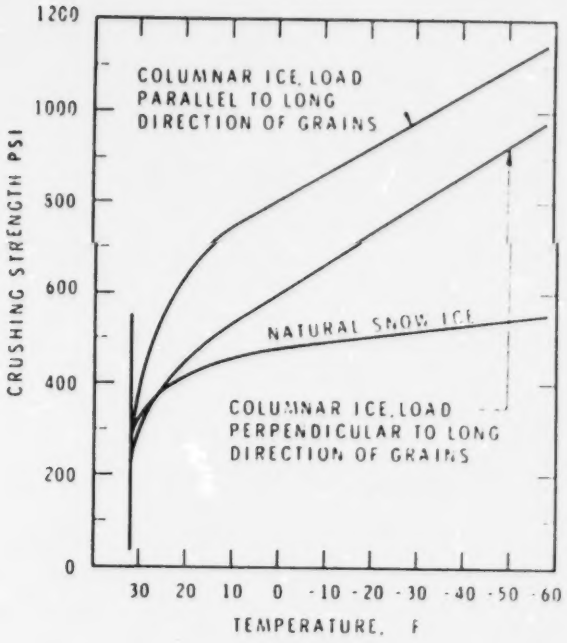


FIGURE 23 /13/

CRUSHING STRENGTH OF ICE AT DIFFERENT TEMPERATURES
1 psi ≃ 0.1417 kip/ft for 12" thick ice
1 psi ≃ 0.2126 kip/ft for 18" thick ice

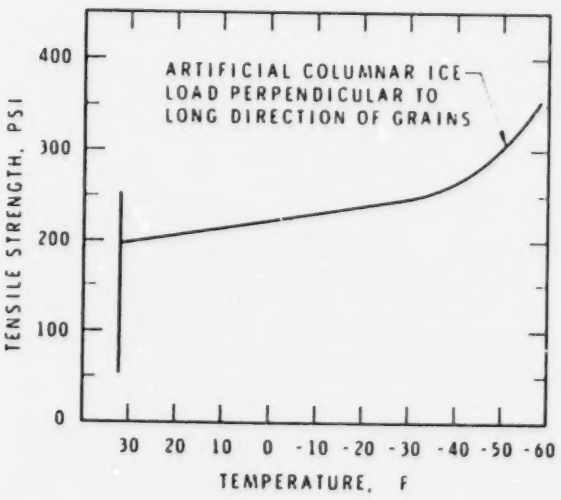


FIGURE 24 /13/

TENSILE STRENGTH OF ICE AT DIFFERENT TEMPERATURES

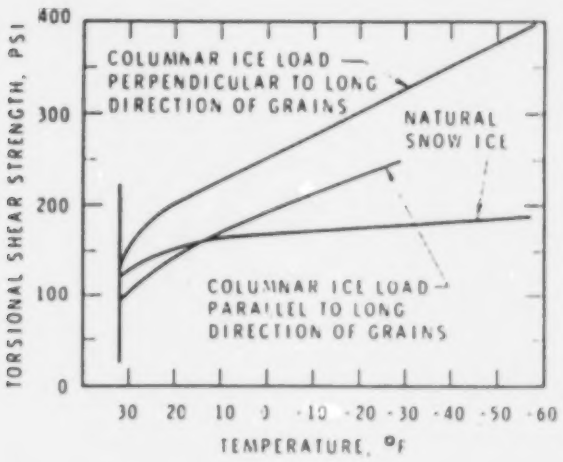

TORSIONAL SHEAR STRENGTH, PSI
400
300
200
100
0
COLUMNAR ICE LOAD — PERPENDICULAR TO LONG DIRECTION OF GRAINS
NATURAL SNOW ICE
COLUMNAR ICE LOAD — PARALLEL TO LONG DIRECTION OF GRAINS
30 20 10 0 -10 -20 -30 -40 -50 -60
TEMPERATURE, °F

FIGURE 25 /13/

TORSIONAL STRENGTH OF ICE
AT DIFFERENT TEMPERATURES

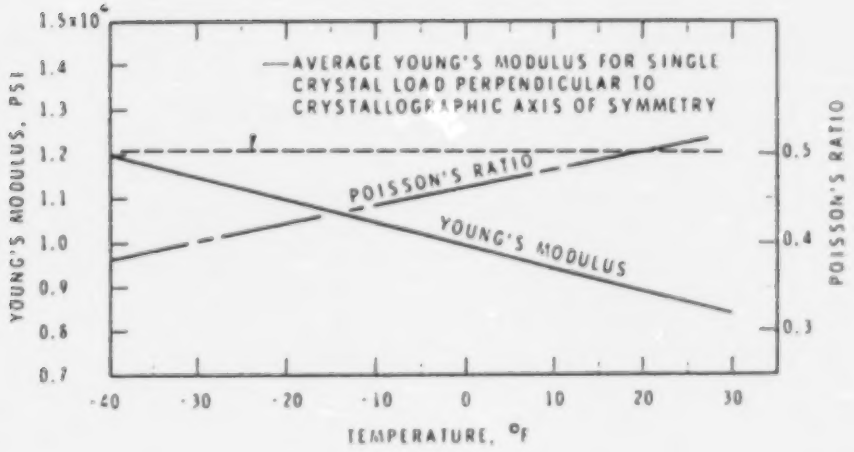


FIGURE 26 /13/

DEPENDENCE OF YOUNG'S MODULUS AND POISSON'S RATIO ON TEMPERATURE FOR COLUMNAR-GRAINED ICE
(Gold, 1958)
For $\dot{\sigma} \simeq 5$ psi/sec
(1 psi $\simeq$ 6.895 kN/m^2)

APPENDIX A

MUSKOKA: 5 HOUR TEMPERATURE STUDY

Temp. Change (Deg. C)	Month	Da	Year	Start Temp. (Deg. C)	Final Temp. (Deg. C)	Rate Temp. Chang (Deg. C / hr.)	D and M (kips/ft)	Lindgren (kips/ft)
Starting Temp. < -10 C								
14.4	3	10	1953	-23.3	-8.9	2.88	10	37
17.8	3	22	1954	-17.2	0.6	3.56	9	30
21.1	2	5	1955	-16.7	4.4	4.22	9	30
17.8	2	29	1956	-25	-7.2	3.56	13	40
16.1	2	21	1957	-19.4	-3.3	3.22	8	35
13.9	12	4	1957	-20.6	-6.7	2.78	8	34
19.4	3	11	1959	-22.2	-2.8	3.88	11	36
21.1	3	9	1960	-24.4	-3.3	4.22	12	40
17.8	2	5	1961	-21.7	-3.9	3.56	10	36
18.3	3	2	1962	-31.1	-12.8	3.66	13	45
19.5	2	16	1963	-32.8	-13.3	3.9	12	45
18.9	2	22	1964	-25.6	-6.7	3.78	12	40
17.2	1	19	1965	-26.1	-8.9	3.44	11	40
16.7	1	22	1966	-20.6	-3.9	3.34	9	36
19.5	2	26	1967	-25.6	-6.1	3.9	13	40
20.5	1	12	1968	-33.3	-12.8	4.1	14	45
18.9	2	16	1969	-21.1	-2.2	3.78	10	36
19.5	2	4	1970	-35.6	-16.1	3.9	14	45
20	1	8	1971	-33.3	-13.3	4	14	45
19.5	2	25	1972	-26.7	-7.2	3.9	12	40
22.2	2	13	1973	-27.2	-5	4.44	13	40
20	2	15	1974	-30.6	-10.6	4	14	45
22.2	3	9	1975	-29.4	-7.2	4.44	15	45
17.2	2	9	1976	-23.3	-6.1	3.44	10	36
17.2	12	3	1976	-30	-12.8	3.44	11	45
20.6	3	8	1978	-25	-4.4	4.12	13	40
20.7	2	18	1979	-38.9	-18.2	4.14	10	45
21.8	3	2	1980	-33.9	-12.1	4.36	12	45
18.7	1	12	1981	-36.8	-18.1	3.74	10	45
21	2	26	1982	-27.1	-6.1	4.2	13	40
19.5	1	21	1983	-20.7	-1.2	3.9	10	36
19.3	3	4	1984	-22.6	-3.3	3.86	10	36
19.9	3	6	1985	-25.4	-5.5	3.98	13	40
16.4	2	11	1986	-26.3	-9.9	3.28	11	40
19.8	2	20	1987	-24.1	-4.3	3.96	13	40
18.5	2	28	1988	-21.3	-2.8	3.7	10	36
19.5	2	18	1989	-31.3	-11.8	3.9	14	45
34.3	12	16	1989	-19.1	15.2	6.86		36
						Average Pressure	11.51351	39.73684
						Std. Deviation	1.854455	4.326687

MUSKOKA: 5 HOUR TEMPERATURE STUDY

Temp. Change (Deg. C)	Month	Da	Year	Start Temp. (Deg. C)	Final Temp. (Deg. C)	Rate Temp. Chang (Deg. C / hr.)	D and M (kips/ft)	Lindgren (kips/ft)
Starting Temp. < -20 C								
14.4	3	10	1953	-23.3	-8.9	2.88	10	39
17.8	1	13	1954	-30.6	-12.8	3.56	12	45
15.5	2	4	1955	-28.3	-12.8	3.1	11	41
17.8	2	29	1956	-25	-7.2	3.56	12	40
15	2	21	1957	-20	-5	3	9	35
13.9	12	4	1957	-20.6	-6.7	2.78	8	34
19.4	3	11	1959	-22.2	-2.8	3.88	11	36
21.1	3	9	1960	-24.4	-3.3	4.22	13	40
17.8	2	5	1961	-21.7	-3.9	3.56	10	36
18.3	3	2	1962	-31.1	-12.8	3.66	13	45
19.5	2	16	1963	-32.8	-13.3	3.9	13	45
18.9	2	22	1964	-25.6	-6.7	3.78	12	40
17.2	1	19	1965	-26.1	-8.9	3.44	11	40
16.7	1	22	1966	-20.6	-3.9	3.34	10	36
19.5	2	26	1967	-25.6	-6.1	3.9	12	40
20.5	1	12	1968	-33.3	-12.8	4.1	14	45
18.9	2	16	1969	-21.1	-2.2	3.78	10	36
19.5	2	4	1970	-35.6	-16.1	3.9	15	45
20	1	8	1971	-33.3	-13.3	4	15	45
19.5	2	25	1972	-26.7	-7.2	3.9	13	40
22.2	2	13	1973	-27.2	-5	4.44	13	40
20	2	15	1974	-30.6	-10.6	4	14	45
22.2	3	9	1975	-29.4	-7.2	4.44	13	45
17.2	2	9	1976	-23.3	-6.1	3.44	10	36
17.2	12	3	1976	-30	-12.8	3.44	13	45
20.6	3	8	1978	-25	-4.4	4.12	13	40
20.7	2	18	1979	-38.9	-18.2	4.14	10	45
21.8	3	2	1980	-33.9	-12.1	4.36	14	45
18.7	1	12	1981	-36.8	-18.1	3.74	9	45
21	2	26	1982	-27.1	-6.1	4.2	13	40
19.5	1	21	1983	-20.7	-1.2	3.9	10	36
19.3	3	4	1984	-22.6	-3.3	3.86	10	36
19.9	3	6	1985	-25.4	-5.5	3.98	13	40
16.4	2	11	1986	-26.3	-9.9	3.28	10	40
19.8	2	20	1987	-24.1	-4.3	3.96	13	40
18.5	2	28	1988	-21.3	-2.8	3.7	10	36
19.5	2	18	1989	-31.3	-11.8	3.9	14	45
16.8	12	23	1989	-33.3	-16.5	3.36	11	45
						Average Pressure	11.76315	40.71052
						Std. Deviation	1.783465	3.705670

MUSKOKA: 5 HOUR TEMPERATURE STUDY

Temp. Change (Deg. C)	Month	Da	Year	Start Temp. (Deg. C)	Final Temp. (Deg. C)	Rate Temp. Chang (Deg. C / hr.)	D and M (kips/ft)	Lindgren (kips/ft)
Starting Temp. < -30 C								
0								
17.8	1	13	1954	-30.6	-12.8	3.56	12	43
7.8	1	28	1955	-30	-22.2	1.56	7	37
16.6	12	21	1955	-33.3	-16.7	3.32	12	44
9.4	1	14	1957	-31.1	-21.7	1.88	8	39
0								
18.3	2	20	1959	-34.4	-16.1	3.66	14	43
11.6	1	9	1960	-33.3	-21.7	2.32	8	41
14.5	1	21	1961	-30.6	-16.1	2.9	10	43
18.3	3	2	1962	-31.1	-12.8	3.66	13	43
19.5	2	16	1963	-32.8	-13.3	3.9	13	43
18.3	1	12	1964	-31.1	-12.8	3.66	13	43
15.6	1	17	1965	-33.9	-18.3	3.12	11	43
14.4	1	12	1966	-30	-15.6	2.88	11	43
17.2	1	18	1967	-35	-17.8	3.44	12	43
20.5	1	12	1968	-33.3	-12.8	4.1	14	43
0								
19.5	2	4	1970	-35.6	-16.1	3.9	14	43
20	1	8	1971	-33.3	-13.3	4	15	43
18.3	2	8	1972	-34.4	-16.1	3.66	14	43
17.2	1	8	1973	-35	-17.8	3.44	12	43
20	2	15	1974	-30.6	-10.6	4	14	43
21.7	3	9	1975	-30	-8.3	4.34	15	43
16.7	1	5	1976	-30.6	-13.9	3.34	12	43
17.2	12	3	1976	-30	-12.8	3.44	12	43
16.5	12	11	1977	-32.5	-16	3.3	12	43
20.7	2	18	1979	-38.9	-18.2	4.14	14	43
21.8	3	2	1980	-33.9	-12.1	4.36	14	43
18.7	1	12	1981	-36.8	-18.1	3.74	14	43
19.7	1	10	1982	-35.4	-15.7	3.94	14	43
0								
18.6	3	8	1984	-31.3	-12.7	3.72	13	43
15.4	1	9	1985	-31.4	-16	3.08	11	43
15.9	1	15	1986	-34	-18.1	3.18	12	43
8.7	2	15	1987	-30.3	-21.6	1.74	8	38
18.3	1	7	1988	-32.7	-14.4	3.66	12	43
19.5	2	18	1989	-31.3	-11.8	3.9	14	43
16.8	12	23	1989	-33.3	-16.5	3.36	11	43
						Average Pressure	12.20588	42.52941
						Std. Deviation	2.040464	1.479970

MUSKOKA: 10 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M kips/ft	Lindgren kips/ft
Start Temp. < -10 C								
18.4	3	8	1953	-26.7	-8.3	1.84	13	34
20.6	1	13	1954	-30.6	-10	2.06	17	39
42.8	12	29	1954	-17.8	25	4.28		
20.6	2	29	1956	-25	-4.4	2.06	16	34
18.9	2	21	1957	-20	-1.1	1.89	14	29
18.9	1	9	1958	-23.3	-4.4	1.89	15	30
23.9	2	25	1959	-27.2	-3.3	2.39	18	39
22.2	3	9	1960	-23.9	-1.7	2.22	17	34
21.7	3	18	1961	-21.1	0.6	2.17	14	31
20.6	3	2	1962	-30.6	-10	2.06	18	39
22.2	2	16	1963	-33.3	-11.1	2.22	18	40
20.6	2	22	1964	-25.6	-5	2.06	16	35
20.6	1	17	1965	-35	-14.4	2.06	18	39
17.8	1	22	1966	-20.6	-2.8	1.78	13	29
18.9	2	26	1967	-25.6	-6.7	1.89	15	34
23.3	1	12	1968	-32.2	-8.9	2.33	18	40
20	2	16	1969	-20.6	-0.6	2	14	30
22.7	3	19	1970	-13.3	9.4	2.27	10	26
22.2	1	17	1971	-35	-12.8	2.22	18	40
21.1	2	10	1972	-28.9	-7.8	2.11	18	39
25.6	2	13	1973	-26.7	-1.1	2.56	19	37
22.3	2	15	1974	-30.6	-8.3	2.23	18	40
25.6	3	9	1975	-28.9	-3.3	2.56	21	41
19.5	1	5	1976	-30.6	-11.1	1.95	17	39
21.9	1	18	1977	-38.1	-16.2	2.19	19	40
23.4	3	9	1978	-20	3.4	2.34	14	31
25	2	18	1979	-38.9	-13.9	2.5	20	40
24.3	3	2	1980	-33.9	-9.6	2.43	18	40
22.4	1	12	1981	-37.2	-14.8	2.24	19	40
22.7	2	26	1982	-27.1	-4.4	2.27	17	36
24.1	3	26	1983	-19.9	4.2	2.41	14	32
23.1	2	1	1984	-31.7	-8.6	2.31	18	40
22	3	6	1985	-25.4	-3.4	2.2	17	36
22.6	1	8	1986	-31.2	-8.6	2.26	18	40
24.7	2	5	1987	-27.4	-2.7	2.47	19	37
21.4	3	22	1988	-25.2	-3.8	2.14	18	36
22.8	2	24	1989	-32.2	-9.4	2.28	18	40
18.2	11	29	1989	-20.4	-2.2	1.82	13	29
						Avg.	16.6756	36.0810
						Std.Dev.	2.33717	4.21950

MUSKOKA: 10 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M kips/ft	Lindgren kips/ft
Start Temp. < -20 C								
18.4	3	8	1953	-26.7	-8.3	1.84	13	34
20.6	1	13	1954	-30.6	-10	2.06	17	39
19.4	2	4	1955	-28.3	-8.9	1.94	17	34
20.6	2	29	1956	-25	-4.4	2.06	16	34
18.9	2	21	1957	-20	-1.1	1.89	14	29
18.9	1	9	1958	-23.3	-4.4	1.89	15	30
23.9	2	25	1959	-27.2	-3.3	2.39	18	39
22.2	3	9	1960	-23.9	-1.7	2.22	17	34
21.7	3	18	1961	-21.1	0.6	2.17	14	31
20.6	3	2	1962	-30.6	-10	2.06	18	39
22.2	2	16	1963	-33.3	-11.1	2.22	18	40
20.6	2	22	1964	-25.6	-5	2.06	16	35
20.6	1	17	1965	-35	-14.4	2.06	18	39
17.8	1	22	1966	-20.6	-2.8	1.78	13	29
18.9	2	26	1967	-25.6	-6.7	1.89	15	34
23.3	1	12	1968	-32.2	-8.9	2.33	18	40
20	2	16	1969	-20.6	-0.6	2	14	30
20.6	1	22	1970	-32.8	-12.2	2.06	17	40
22.2	1	17	1971	-35	-12.8	2.22	18	40
21.1	2	10	1972	-28.9	-7.8	2.11	18	39
25.6	2	13	1973	-26.7	-1.1	2.56	19	37
22.3	2	15	1974	-30.6	-8.3	2.23	18	40
25.6	3	9	1975	-28.9	-3.3	2.56	21	41
19.5	1	5	1976	-30.6	-11.1	1.95	17	39
21.9	1	18	1977	-38.1	-16.2	2.19	19	40
23.4	3	9	1978	-20	3.4	2.34	14	31
25	2	18	1979	-38.9	-13.9	2.5	20	40
24.3	3	2	1980	-33.9	-9.6	2.43	18	40
22.4	1	12	1981	-37.2	-14.8	2.24	19	40
22.7	2	26	1982	-27.1	-4.4	2.27	17	36
23.3	3	25	1983	-24.3	-1	2.33	18	36
23.1	2	1	1984	-31.7	-8.6	2.31	18	40
22	3	6	1985	-25.4	-3.4	2.2	17	36
22.6	1	8	1986	-31.2	-8.6	2.26	18	40
24.7	2	5	1987	-27.4	-2.7	2.47	19	37
21.4	3	22	1988	-25.2	-3.8	2.14	18	36
22.8	2	24	1989	-32.2	-9.4	2.28	18	40
18.2	11	29	1989	-20.4	-2.2	1.82	13	29
						Avg.	16.9736	36.5
						Std.Dev.	1.97998	3.81651

MUSKOKA: 10 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M kips/ft	Lindgren kips/ft
Start Temp. < -30 C								
0								
20.6	1	13	1954	-30.6	-10	2.06	17	40
13.3	1	28	1955	-30	-16.7	1.33	14	39
18.9	12	21	1955	-33.9	-15	1.89	15	39
12.8	1	14	1957	-31.1	-18.3	1.28	10	35
0								
22.8	2	22	1959	-30	-7.2	2.28	19	40
13.9	1	9	1960	-33.3	-19.4	1.39	10	35
15	2	2	1961	-30.6	-15.6	1.5	14	37
20.6	3	2	1962	-30.6	-10	2.06	18	39
22.2	2	16	1963	-33.3	-11.1	2.22	18	40
18.9	1	12	1964	-30.6	-11.7	1.89	17	39
20.6	1	17	1965	-35	-14.4	2.06	18	39
16.1	1	29	1966	-31.7	-15.6	1.61	14	37
18.3	2	3	1967	-30	-11.7	1.83	17	39
23.3	1	12	1968	-32.2	-8.9	2.33	18	40
0								
20.6	1	22	1970	-32.8	-12.2	2.06	17	40
22.2	1	17	1971	-35	-12.8	2.22	18	40
20.5	1	16	1972	-38.3	-17.8	2.05	16	40
19.4	2	9	1973	-30	-10.6	1.94	18	39
22.3	2	15	1974	-30.6	-8.3	2.23	18	40
25	3	9	1975	-30	-5	2.5	21	41
19.5	1	5	1976	-30.6	-11.1	1.95	17	39
21.9	1	18	1977	-38.1	-16.2	2.19	19	40
16.9	12	11	1977	-31.9	-15	1.69	14	37
25	2	18	1979	-38.9	-13.9	2.5	20	40
24.3	3	2	1980	-33.9	-9.6	2.43	18	40
22.4	1	12	1981	-37.2	-14.8	2.24	19	40
22.3	1	12	1982	-39.1	-16.8	2.23	19	40
0								
23.1	2	1	1984	-31.7	-8.6	2.31	18	40
17.1	1	9	1985	-30.9	-13.8	1.71	14	37
22.6	1	8	1986	-31.2	-8.6	2.26	18	40
13.1	2	15	1987	-30.6	-17.5	1.31	13	35
21	1	27	1988	-30.4	-9.4	2.1	18	40
22.8	2	24	1989	-32.2	-9.4	2.28	18	40
15.7	12	23	1989	-32.4	-16.7	1.57	14	37
						Avg.	16.6470	38.9117
						Std.Dev.	2.55391	1.61550

MUSKOKA: 20 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M kips/ft	Lindgren kips/ft
Start Temp. < -10 C								
18.3	1	18	1953	-16.1	2.2	0.915	14	19
21.6	2	13	1954	-29.4	-7.8	1.08	19	32
23.3	2	5	1955	-18.9	4.4	1.165	–	–
20	2	24	1956	-24.4	-4.4	1	19	28
18.9	1	4	1957	-22.8	-3.9	0.945	16	24
21.2	12	13	1957	-25.6	-4.4	1.06	19	28
24.4	2	23	1959	-30	-5.6	1.22	22	34
22.8	2	9	1960	-22.8	0	1.14	21	25
18.9	12	14	1960	-26.7	-7.8	0.945	18	28
19.4	2	2	1962	-33.3	-13.9	0.97	18	32
20	2	17	1963	-33.3	-13.3	1	18	33
21.1	2	25	1964	-22.2	-1.1	1.055	18	25
23.3	1	18	1965	-35	-11.7	1.165	19	34
21.6	1	10	1966	-22.2	-0.6	1.08	20	24
20.6	2	4	1967	-30	-9.4	1.03	18	33
18.9	1	6	1968	-28.3	-9.4	0.945	18	32
18.4	1	28	1969	-25.6	-7.2	0.92	18	27
23.4	2	5	1970	-35.6	-12.2	1.17	21	34
19.5	1	2	1971	-20.6	-1.1	0.975	18	25
26.1	1	9	1972	-26.7	-0.6	1.305	23	31
20.5	1	9	1973	-27.2	-6.7	1.025	19	28
21.6	2	19	1974	-24.4	-2.8	1.08	18	28
21.7	3	10	1975	-30	-8.3	1.085	20	32
23.4	2	24	1976	-26.7	-3.3	1.17	21	30
30	12	14	1976	-26.7	3.3	1.5	24	32
20.4	1	4	1978	-24.2	-3.8	1.02	19	28
22.7	2	7	1979	-35.7	-13	1.135	19	34
21.9	2	18	1980	-30.2	-8.3	1.095	19	33
22.4	12	18	1980	-25.2	-2.8	1.12	21	30
18.5	1	27	1982	-26.7	-8.2	0.925	18	28
19.4	12	13	1982	-24.5	-5.1	0.97	18	28
16.1	12	21	1983	-26.5	-10.4	0.805	14	26
18.7	12	28	1984	-11.3	7.4	0.935	9	16
16.4	1	16	1986	-25.1	-8.7	0.82	14	26
15.8	2	16	1987	-21.2	-5.4	0.79	14	23
18.4	1	29	1988	-22.6	-4.2	0.92	17	24
16.9	3	13	1989	-17.6	-0.7	0.845	15	26
26.8	12	16	1989	-11.6	15.2	1.34	–	–
						Avg.	18.22222	28.33333
						Std.Dev.	2.819683	4.249182

MUSKOKA: 20 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M kips/ft	Lindgren kips/ft
Start Temp. < -20 C								
16.1	3	8	1953	-26.7	-10.6	0.805	14	26
21.6	2	13	1954	-29.4	-7.8	1.08	19	32
21.7	12	23	1954	-25.6	-3.9	1.085	20	28
20	2	24	1956	-24.4	-4.4	1	19	28
18.9	1	4	1957	-22.8	-3.9	0.945	16	24
21.2	12	13	1957	-25.6	-4.4	1.06	19	28
24.4	2	23	1959	-30	-5.6	1.22	22	34
22.8	2	9	1960	-22.8	0	1.14	21	25
18.9	12	14	1960	-26.7	-7.8	0.945	18	26
19.4	2	2	1962	-33.3	-13.9	0.97	18	32
20	2	17	1963	-33.3	-13.3	1	18	33
21.1	2	25	1964	-22.2	-1.1	1.055	18	25
23.3	1	18	1965	-35	-11.7	1.165	19	34
21.6	1	10	1966	-22.2	-0.6	1.08	20	24
20.6	2	4	1967	-30	-9.4	1.03	18	33
18.9	1	6	1968	-28.3	-9.4	0.945	18	32
18.4	1	28	1969	-25.6	-7.2	0.92	18	27
23.4	2	5	1970	-35.6	-12.2	1.17	21	34
19.5	1	2	1971	-20.6	-1.1	0.975	18	25
26.1	1	9	1972	-26.7	-0.6	1.305	23	31
20.5	1	9	1973	-27.2	-6.7	1.025	19	28
21.6	2	19	1974	-24.4	-2.8	1.08	18	28
21.7	3	10	1975	-30	-8.3	1.085	20	32
23.4	2	24	1976	-26.7	-3.3	1.17	21	30
30	12	14	1976	-26.7	3.3	1.5	24	32
20.4	1	4	1978	-24.2	-3.8	1.02	19	28
22.7	2	7	1979	-35.7	-13	1.135	19	34
21.9	2	18	1980	-30.2	-8.3	1.095	19	33
22.4	12	18	1980	-25.2	-2.8	1.12	21	30
18.5	1	27	1982	-26.7	-8.2	0.925	18	28
19.4	12	13	1982	-24.5	-5.1	0.97	18	28
16.1	12	21	1983	-26.5	-10.4	0.805	14	26
15.8	1	16	1985	-27.2	-11.4	0.79	14	26
16.4	1	16	1986	-25.1	-8.7	0.82	14	26
15.8	2	16	1987	-21.2	-5.4	0.79	14	23
18.4	1	29	1988	-22.6	-4.2	0.92	17	24
15.3	2	25	1989	-21.7	-6.4	0.765	14	22
17.2	12	27	1989	-30.3	-13.1	0.86	16	32
						Avg.	18.31578	28.76315
						Std.Dev.	2.482626	3.490092

MUSKOKA: 20 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M kips/ft	Lindgren kips/ft
Start Temp. < -30 C								
0								
15	1	14	1954	-30.6	-15.6	0.75	14	30
16.7	1	28	1955	-30	-13.3	0.835	15	32
15	12	22	1955	-33.3	-18.3	0.75	15	32
11.2	1	16	1957	-30.6	-19.4	0.56	9	29
0								
24.4	2	23	1959	-30	-5.6	1.22	22	34
18.3	1	10	1960	-33.3	-15	0.915	16	32
15	1	22	1961	-30.6	-15.6	0.75	14	30
19.4	2	2	1962	-33.3	-13.9	0.97	18	32
20	2	17	1963	-33.3	-13.3	1	18	33
18.9	12	31	1963	-32.8	-13.9	0.945	17	32
23.3	1	18	1965	-35	-11.7	1.165	19	34
14.5	1	30	1966	-30.6	-16.1	0.725	14	30
20.6	2	4	1967	-30	-9.4	1.03	18	33
18.9	1	13	1968	-32.8	-13.9	0.945	17	32
0								
23.4	2	5	1970	-35.6	-12.2	1.17	21	34
18.9	1	13	1971	-32.2	-13.3	0.945	17	32
26.1	1	17	1972	-38.3	-12.2	1.305	23	35
18.3	2	10	1973	-30	-11.7	0.915	17	32
17.8	2	16	1974	-30.6	-12.8	0.89	16	32
21.7	3	10	1975	-30	-8.3	1.085	20	32
17.2	1	6	1976	-30	-12.8	0.86	16	32
28.5	1	19	1977	-38.5	-10	1.425	25	36
14.3	12	12	1977	-32.5	-18.2	0.715	15	30
22.7	2	7	1979	-35.7	-13	1.135	19	34
21.9	2	18	1980	-30.2	-8.3	1.095	19	33
17.4	1	12	1981	-32.2	-14.8	0.87	15	32
17.4	1	13	1982	-30.3	-12.9	0.87	16	32
0								
16	1	16	1984	-31.2	-15.2	0.8	14	31
0								
0								
0								
0								
0								
17.2	12	27	1989	-30.3	-13.1	0.86	16	32
						Avg.	17.06896	32.20689
						Std.Dev.	3.139635	1.539800

NORTH BAY: 5 HOUR TEMPERATURE STUDY

Temp. Change (Deg. C)	Month	Day	Year	Start Temp. (Deg. C)	Final Temp. (Deg. C)	Rate Temp. Chang (Deg. C / hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -10 C								
12.7	1	12	1953	-19.4	-6.7	2.54	8	32
12.8	1	13	1954	-27.8	-15	2.56	8	37
13.9	2	4	1955	-23.3	-9.4	2.78	9	34
11.7	1	9	1956	-13.9	-2.2	2.34	6	26
15.6	2	28	1957	-16.7	-1.1	3.12	9	29
12.2	1	12	1958	-22.2	-10	2.44	7	32
12.3	3	10	1959	-20.6	-8.3	2.46	7	32
14.5	3	7	1960	-22.8	-8.3	2.9	9	35
13.3	1	5	1961	-22.2	-8.9	2.66	8	34
11.1	2	10	1962	-31.1	-20	2.22	8	39
12.2	3	16	1963	-12.8	-0.6	2.44	6	26
11.6	2	29	1964	-12.2	-0.6	2.32	6	26
12.8	1	21	1965	-20	-7.2	2.56	8	32
10.6	1	12	1966	-30	-19.4	2.12	8	39
12.2	2	26	1967	-20	-7.8	2.44	7	32
12.3	2	4	1968	-15.6	-3.3	2.46	8	28
11.1	2	14	1969	-19.4	-8.3	2.22	7	31
11.2	2	4	1970	-30.6	-19.4	2.24	8	39
10	2	14	1971	-18.9	-8.9	2	6	30
13.4	3	7	1972	-10.6	2.8	2.68	5	23
11.1	1	21	1973	-19.4	-8.3	2.22	7	31
11.1	2	5	1974	-26.7	-15.6	2.22	7	35
11.7	3	28	1975	-13.9	-2.2	2.34	6	26
11.7	1	31	1976	-21.1	-9.4	2.34	7	31
11.1	12	10	1976	-10	1.1	2.22	5	21
10.6	3	15	1978	-19.3	-8.7	2.12	6	30
11.4	2	25	1979	-21.7	-10.3	2.28	6	32
10.8	2	10	1980	-18.2	-7.4	2.16	6	30
11.4	12	18	1980	-13.2	-1.8	2.28	6	26
11.7	1	10	1982	-35.8	-24.1	2.34	8	41
13.8	1	4	1983	-22.2	-8.4	2.76	9	34
12.5	1	21	1984	-29.7	-17.2	2.5	8	41
9.8	12	7	1984	-26.3	-16.5	1.96	7	34
11.6	2	22	1986	-19.9	-8.3	2.32	6	32
12.6	2	16	1987	-24.4	-11.8	2.52	9	36
11.1	1	7	1988	-25.9	-14.8	2.22	7	35
11.2	2	9	1989	-26.7	-15.5	2.24	7	35
10.3	12	4	1989	-25.2	-14.9	2.06	7	34
						Avg. Press.	7.15789	32.10526
						Std. Dev.	1.11275	4.666732

NORTH BAY: 5 HOUR TEMPERATURE STUDY

Temp. Change (Deg. C)	Month	Day	Year	Start Temp. (Deg. C)	Final Temp. (Deg. C)	Rate Temp. Chang (Deg. C / hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -20								
11.1	3	8	1953	-22.2	-11.1	2.22	6	31
12.8	1	13	1954	-27.8	-15	2.56	8	37
13.9	2	4	1955	-23.3	-9.4	2.78	9	34
11.1	12	23	1955	-22.2	-11.1	2.22	6	31
12.7	1	2	1957	-28.3	-15.6	2.54	8	41
12.2	1	12	1958	-22.2	-10	2.44	7	32
12.3	3	10	1959	-20.6	-8.3	2.46	7	32
14.5	3	7	1960	-22.8	-8.3	2.9	9	35
13.3	1	5	1961	-22.2	-8.9	2.66	8	34
11.1	2	10	1962	-31.1	-20	2.22	8	39
11.2	2	12	1963	-20.6	-9.4	2.24	6	31
11.1	2	27	1964	-22.8	-11.7	2.22	6	31
12.8	1	21	1965	-20	-7.2	2.56	8	32
10.6	1	12	1966	-30	-19.4	2.12	8	39
12.2	2	26	1967	-20	-7.8	2.44	7	32
11.1	3	3	1968	-21.1	-10	2.22	6	31
8.9	2	14	1969	-20	-11.1	1.78	6	29
11.2	2	4	1970	-30.6	-19.4	2.24	8	39
9.4	1	13	1971	-28.3	-18.9	1.88	7	30
11.1	1	8	1972	-26.1	-15	2.22	7	35
10	2	11	1973	-25	-15	2	7	34
11.1	2	5	1974	-26.7	-15.6	2.22	7	35
10	1	20	1975	-30	-20	2	8	39
11.7	1	31	1976	-21.1	-9.4	2.34	7	31
11.1	12	24	1976	-23.3	-12.2	2.22	6	31
10.2	3	2	1978	-20.1	-9.9	2.04	6	30
11.4	2	25	1979	-21.7	-10.3	2.28	6	32
9.7	3	2	1980	-24.5	-14.8	1.94	7	34
11.3	12	17	1980	-32.5	-21.2	2.26	8	40
11.7	1	10	1982	-35.8	-24.1	2.34	8	41
13.8	1	4	1983	-22.2	-8.4	2.76	9	34
12.5	1	21	1984	-29.7	-17.2	2.5	8	41
9.8	12	7	1984	-26.3	-16.5	1.96	7	34
10.2	2	6	1986	-23.8	-13.6	2.04	7	31
12.6	2	16	1987	-24.4	-11.8	2.52	9	36
11.1	1	7	1988	-25.9	-14.8	2.22	7	35
11.2	2	9	1989	-26.7	-15.5	2.24	7	35
10.3	12	4	1989	-25.2	-14.9	2.06	7	34
						Avg. Press.	7.26315	34.26315
						Std. Dev.	0.93707	3.431159

NORTH BAY: 5 HOUR TEMPERATURE STUDY

Temp. Change (Deg. C)	Month	Day	Year	Start Temp. (Deg. C)	Final Temp. (Deg. C)	Rate Temp. Chang (Deg. C / hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -30 C								
0								
4.4	1	17	1954	-30	-25.6	0.88	4	31
0								
6.7	12	22	1955	-30	-23.3	1.34	5	35
8.9	1	15	1957	-33.3	-24.4	1.78	7	39
0								
7.3	1	6	1959	-30.6	-23.3	1.46	6	36
6.7	1	9	1960	-31.1	-24.4	1.34	5	35
0								
11.1	2	10	1962	-31.1	-20	2.22	8	39
10	1	23	1963	-31.1	-21.1	2	8	39
10	1	12	1964	-30.6	-20.6	2	8	39
7.3	1	16	1965	-30.6	-23.3	1.46	6	36
10.6	1	12	1966	-30	-19.4	2.12	8	39
8.3	2	6	1967	-31.1	-22.8	1.66	7	37
7.8	1	1	1968	-31.1	-23.3	1.56	7	36
6.2	12	25	1968	-30.6	-24.4	1.24	5	34
11.2	2	4	1970	-30.6	-19.4	2.24	8	39
7.8	1	18	1971	-30.6	-22.8	1.56	7	36
8.3	1	16	1972	-34.4	-26.1	1.66	7	37
8.9	1	31	1973	-30.6	-21.7	1.78	7	39
0								
10	1	20	1975	-30	-20	2	8	39
9.4	12	19	1975	-35	-25.6	1.88	8	40
6.9	1	9	1977	-30.9	-24	1.38	5	35
0								
9.4	2	6	1979	-30.2	-20.8	1.88	8	40
0								
11.3	12	17	1980	-32.5	-21.2	2.26	8	39
11.7	1	10	1982	-35.8	-24.1	2.34	8	41
0								
12.3	1	21	1984	-31	-18.7	2.46	9	42
0								
4.9	12	18	1985	-32	-27.1	0.98	5	33
7.5	1	24	1987	-30.3	-22.8	1.5	6	36
8.3	1	14	1988	-31.2	-22.9	1.66	7	37
6.2	1	4	1989	-31.4	-25.2	1.24	5	34
6.8	12	22	1989	-31.2	-24.4	1.36	6	35
						Avg. Press.	6.53333	37.13793
						Std. Dev.	1.76509	2.528787

NORTH BAY: 10 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -10 C								
16.7	1	12	1953	-20	-3.3	1.67	13	28
17.8	2	13	1954	-27.2	-9.4	1.78	13	34
15	12	22	1954	-26.1	-11.1	1.5	12	32
15	3	28	1956	-13.9	1.1	1.5	10	23
18.3	2	28	1957	-18.3	0	1.83	14	29
16.7	12	13	1957	-22.8	-6.1	1.67	12	29
17.2	2	22	1959	-25	-7.8	1.72	13	33
15	12	14	1959	-17.2	-2.2	1.5	10	25
17.3	3	11	1961	-21.7	-4.4	1.73	12	29
15	1	16	1962	-24.4	-9.4	1.5	12	32
18.9	3	11	1963	-21.7	-2.8	1.89	14	29
16.1	3	6	1964	-21.7	-5.6	1.61	12	28
17.3	1	21	1965	-21.7	-4.4	1.73	12	28
13.9	3	11	1966	-16.1	-2.2	1.39	10	23
16.1	2	26	1967	-22.2	-6.1	1.61	12	28
15.6	3	7	1968	-20	-4.4	1.56	12	28
12.8	2	14	1969	-21.1	-8.3	1.28	11	26
16.2	2	4	1970	-30.6	-14.4	1.62	14	37
13.3	4	8	1971	-12.2	1.1	1.33	7	18
16.1	1	8	1972	-26.1	-10	1.61	12	32
13.9	1	21	1973	-18.9	-5	1.39	11	26
15	2	18	1974	-20.6	-5.6	1.5	12	28
17.2	3	28	1975	-15	2.2	1.72	10	24
16.1	1	31	1976	-23.9	-7.8	1.61	12	32
16.8	1	18	1977	-27.9	-11.1	1.68	12	37
14.5	3	20	1978	-15.3	-0.8	1.45	10	23
15	3	13	1979	-11.3	3.7	1.5	11	19
17.4	3	19	1980	-11.1	6.3	1.74	11	20
16.4	2	5	1981	-26.7	-10.3	1.64	12	32
15.8	1	10	1982	-34.6	-18.8	1.58	15	37
16.7	1	4	1983	-25.1	-8.4	1.67	12	33
15	1	21	1984	-31	-16	1.5	14	36
17	12	7	1984	-26.3	-9.3	1.7	12	32
17.4	1	8	1986	-28	-10.6	1.74	16	36
17.5	2	5	1987	-21.7	-4.2	1.75	12	29
17.3	3	5	1988	-20.2	-2.9	1.73	13	29
16.1	2	9	1989	-29.8	-13.7	1.61	14	37
14	12	27	1989	-27.9	-13.9	1.4	14	34
						Avg.	12.10526	29.34210
						Std.Dev.	1.634971	5.027693

NORTH BAY: 10 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -20 C								
16.7	1	12	1953	-20	-3.3	1.67	13	28
17.8	2	13	1954	-27.2	-9.4	1.78	13	34
15	12	22	1954	-26.1	-11.1	1.5	12	32
13.4	3	12	1956	-22.8	-9.4	1.34	9	26
15.5	1	3	1957	-22.2	-6.7	1.55	12	28
16.7	12	13	1957	-22.8	-6.1	1.67	12	29
17.2	2	22	1959	-25	-7.8	1.72	13	33
14.5	3	7	1960	-22.8	-8.3	1.45	12	32
17.3	3	11	1961	-21.7	-4.4	1.73	12	29
15	1	16	1962	-24.4	-9.4	1.5	12	32
18.9	3	11	1963	-21.7	-2.8	1.89	14	29
16.1	3	6	1964	-21.7	-5.6	1.61	12	28
17.3	1	21	1965	-21.7	-4.4	1.73	12	28
13.9	3	27	1966	-20	-6.1	1.39	10	23
16.1	2	26	1967	-22.2	-6.1	1.61	12	28
15.6	3	7	1968	-20	-4.4	1.56	12	28
12.8	2	14	1969	-21.1	-8.3	1.28	11	26
16.2	2	4	1970	-30.6	-14.4	1.62	14	37
13.3	2	3	1971	-23.3	-10	1.33	11	31
16.1	1	8	1972	-26.1	-10	1.61	12	32
13.3	12	17	1972	-20	-6.7	1.33	11	26
15	2	18	1974	-20.6	-5.6	1.5	12	28
15.5	1	23	1975	-22.2	-6.7	1.55	12	28
16.1	1	31	1976	-23.9	-7.8	1.61	12	32
16.8	1	18	1977	-27.9	-11.1	1.68	12	37
13.8	12	28	1977	-23.6	-9.8	1.38	12	27
12.9	2	6	1979	-30.2	-17.3	1.29	13	35
15.3	3	2	1980	-25.2	-9.9	1.53	12	32
16.4	2	5	1981	-26.7	-10.3	1.64	12	32
15.8	1	10	1982	-34.6	-18.8	1.58	15	37
16.7	1	4	1983	-25.1	-8.4	1.67	12	33
15	1	21	1984	-31	-16	1.5	14	36
17	12	7	1984	-26.3	-9.3	1.7	12	32
17.4	1	8	1986	-28	-10.6	1.74	16	36
17.5	2	5	1987	-21.7	-4.2	1.75	12	29
17.3	3	5	1988	-20.2	-2.9	1.73	13	29
16.1	2	9	1989	-29.8	-13.7	1.61	14	37
14	12	27	1989	-27.9	-13.9	1.4	14	34
						Avg.	12.36842	30.86842
						Std.Dev.	1.265348	3.592177

NORTH BAY: 10 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -30 C								
0								
6.1	1	17	1954	-30	-23.9	0.61	7	28
0								
8.9	12	22	1955	-30	-21.1	0.89	8	32
10.5	1	15	1957	-33.3	-22.8	1.05	9	32
0								
9.4	1	6	1959	-30	-20.6	0.94	9	32
8.9	1	9	1960	-31.1	-22.2	0.89	8	32
0								
10	1	29	1962	-30.6	-20.6	1	9	32
12.8	1	23	1963	-31.1	-18.3	1.28	10	35
8.4	1	12	1964	-30.6	-22.2	0.84	8	32
9.4	1	29	1965	-33.3	-23.9	0.94	9	32
11.1	1	12	1966	-31.1	-20	1.11	9	33
11.1	2	12	1967	-35	-23.9	1.11	10	33
9.4	1	11	1968	-30	-20.6	0.94	9	32
3.9	12	25	1968	-30	-26.1	0.39	5	25
16.2	2	4	1970	-30.6	-14.4	1.62	14	37
8.4	1	18	1971	-30.6	-22.2	0.84	8	32
14.4	1	16	1972	-30	-15.6	1.44	14	36
11.7	1	31	1973	-31.1	-19.4	1.17	10	34
0								
14.4	1	20	1975	-32.2	-17.8	1.44	14	36
13.3	1	18	1976	-32.2	-18.9	1.33	11	34
10.6	12	3	1976	-30	-19.4	1.06	9	32
0								
12.9	2	6	1979	-30.2	-17.3	1.29	13	35
0								
16.4	12	17	1980	-32.5	-16.1	1.64	14	37
15.8	1	10	1982	-34.6	-18.8	1.58	15	37
0								
15	1	21	1984	-31	-16	1.5	14	36
0								
5.7	12	18	1985	-32	-26.3	0.57	5	29
10.8	1	24	1987	-31.7	-20.9	1.08	9	32
12.8	1	14	1988	-32.4	-19.6	1.28	9	35
7.4	1	4	1989	-31.4	-24	0.74	5	30
7.8	12	22	1989	-31.3	-23.5	0.78	5	30
						Avg.	9.620689	32.82758
						Std.Dev.	2.905568	2.767657

NORTH BAY: 20 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp. (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -10 C								
17.2	3	11	1953	-14.4	2.8	0.86	14	20
18.9	2	14	1954	-27.2	-8.3	0.945	19	27
21.1	12	23	1954	-26.1	-5	1.055	19	28
17.8	1	9	1956	-15.6	2.2	0.89	14	20
21.2	12	19	1956	-25.6	-4.4	1.06	19	28
18.9	12	14	1957	-22.8	-3.9	0.945	18	24
20	12	22	1958	-20.6	-0.6	1	18	24
16.6	12	15	1959	-17.2	-0.6	0.83	16	19
18.9	12	14	1960	-27.2	-8.3	0.945	15	27
17.8	2	5	1962	-15	2.8	0.89	14	20
15.6	2	4	1963	-27.8	-12.2	0.78	14	26
20.5	3	7	1964	-21.1	-0.6	1.025	18	24
19.5	1	22	1965	-21.7	-2.2	0.975	17	24
17.8	1	3	1966	-17.2	0.6	0.89	16	19
17.3	2	10	1967	-21.7	-4.4	0.865	15	23
15.6	1	2	1968	-26.7	-11.1	0.78	14	26
16.1	12	1	1968	-16.7	-0.6	0.805	15	19
16.7	1	31	1970	-26.1	-9.4	0.835	14	26
15	2	3	1971	-25	-10	0.75	14	25
23.3	1	9	1972	-26.1	-2.8	1.165	22	29
19.4	12	18	1972	-24.4	-5	0.97	19	28
17.3	12	25	1973	-15.6	1.7	0.865	14	20
21.7	1	18	1975	-28.9	-7.2	1.085	19	32
21.7	2	13	1976	-20	1.7	1.085	18	24
25	12	14	1976	-25	0	1.25	23	31
13.4	1	4	1978	-20.8	-7.4	0.67	13	21
18	3	13	1979	-12.9	5.1	0.9	13	17
16.7	1	11	1980	-16.1	0.6	0.835	15	19
30.5	12	18	1980	-32.5	-2	1.525	27	36
20	1	11	1982	-37.7	-17.7	1	20	34
22.1	1	5	1983	-24.4	-2.3	1.105	19	29
19.4	12	26	1983	-29.9	-10.5	0.97	18	32
25.2	12	8	1984	-26.3	-1.1	1.26	23	30
23.4	1	9	1986	-28	-4.6	1.17	23	30
21.2	12	14	1986	-26.6	-5.4	1.06	19	28
20.9	2	22	1988	-28.5	-7.6	1.045	19	32
22.8	1	22	1989	-26.5	-3.7	1.14	20	29
18.2	11	30	1989	-23.1	-4.9	0.91	19	28
						Avg.	17.52631	25.73684
						Std.Dev.	3.258485	4.733332

NORTH BAY: 20 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp. (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -20 C								
16.1	1	13	1953	-20	-3.9	0.805	14	23
18.9	2	14	1954	-27.2	-8.3	0.945	19	27
21.1	12	23	1954	-26.1	-5	1.055	19	28
16.1	12	2	1955	-20	-3.9	0.805	14	23
21.2	12	19	1956	-25.6	-4.4	1.06	19	28
18.9	12	14	1957	-22.8	-3.9	0.945	18	24
20	12	22	1958	-20.6	-0.6	1	18	24
16.2	2	9	1960	-20.6	-4.4	0.81	14	23
18.9	12	14	1960	-27.2	-8.3	0.945	15	27
15.6	2	2	1962	-30	-14.4	0.78	14	26
15.6	2	4	1963	-27.8	-12.2	0.78	14	26
20.5	3	7	1964	-21.1	-0.6	1.025	18	24
19.5	1	22	1965	-21.7	-2.2	0.975	17	24
17.3	1	10	1966	-21.7	-4.4	0.865	14	23
17.3	2	10	1967	-21.7	-4.4	0.865	15	23
15.6	1	2	1968	-26.7	-11.1	0.78	14	26
12.8	12	26	1968	-28.9	-16.1	0.64	13	27
16.7	1	31	1970	-26.1	-9.4	0.835	14	26
15	2	3	1971	-25	-10	0.75	14	25
23.3	1	9	1972	-26.1	-2.8	1.165	22	29
19.4	12	18	1972	-24.4	-5	0.97	19	28
15	12	23	1973	-25	-10	0.75	14	26
21.7	1	18	1975	-28.9	-7.2	1.085	19	32
21.7	2	13	1976	-20	1.7	1.085	18	24
25	12	14	1976	-25	0	1.25	23	31
13.4	1	4	1978	-20.8	-7.4	0.67	13	21
14.7	12	30	1978	-22.9	-8.2	0.735	13	22
13.5	2	18	1980	-22.9	-9.4	0.675	13	22
30.5	12	18	1980	-32.5	-2	1.525	27	36
20	1	11	1982	-37.7	-17.7	1	20	34
22.1	1	5	1983	-24.4	-2.3	1.105	19	29
19.4	12	26	1983	-29.9	-10.5	0.97	18	32
25.2	12	8	1984	-26.3	-1.1	1.26	23	30
23.4	1	9	1986	-28	-4.6	1.17	23	30
21.2	12	14	1986	-26.6	-5.4	1.06	19	28
20.9	2	22	1988	-28.5	-7.6	1.045	19	32
22.8	1	22	1989	-26.5	-3.7	1.14	20	29
18.2	11	30	1989	-23.1	-4.9	0.91	19	28
						Avg.	17.31578	26.84210
						Std.Dev.	3.442040	3.535729

NORTH BAY: 20 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp. (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -30 C								
0								
10	1	18	1954	-31.1	-21.1	0.5	9	27
0								
8.3	12	22	1955	-30	-21.7	0.415	9	25
12.8	12	31	1956	-31.1	-18.3	0.64	10	29
0								
6.2	1	7	1959	-30.6	-24.4	0.31	5	23
13.9	1	10	1960	-31.1	-17.2	0.695	12	30
0								
15.6	2	2	1962	-30	-14.4	0.78	14	31
6.1	1	1	1963	-30	-23.9	0.305	5	23
8.4	1	13	1964	-30.6	-22.2	0.42	9	25
14.5	1	30	1965	-30.6	-16.1	0.725	13	30
12.8	1	13	1966	-31.1	-18.3	0.64	10	29
17.3	1	19	1967	-30.6	-13.3	0.865	15	32
12.2	1	2	1968	-31.1	-18.9	0.61	10	29
3.4	12	26	1968	-30.6	-27.2	0.17	3	20
16.7	2	5	1970	-30.6	-13.9	0.835	14	31
9.5	1	19	1971	-30.6	-21.1	0.475	9	26
23.3	1	17	1972	-34.4	-11.1	1.165	18	34
10.6	2	1	1973	-30.6	-20	0.53	9	25
0								
18.9	1	21	1975	-31.1	-12.2	0.945	17	32
18.3	1	19	1976	-32.2	-13.9	0.915	16	32
20.3	1	18	1977	-30.6	-10.3	1.015	18	34
0								
13.1	2	7	1979	-30.2	-17.1	0.655	12	30
0								
30.5	12	18	1980	-32.5	-2	1.525	27	36
20	1	11	1982	-37.7	-17.7	1	20	34
0								
18.3	12	26	1983	-30.5	-12.2	0.915	16	32
0								
11.8	12	19	1985	-31	-19.2	0.59	9	25
10.8	1	24	1987	-31.8	-21	0.54	9	25
18.4	1	15	1988	-32.4	-14	0.92	14	32
7.9	1	5	1989	-31.4	-23.5	0.395	5	23
17.3	12	27	1989	-31.4	-14.1	0.865	14	31
						Avg.	11.32258	28.79310
						Std.Dev.	5.738309	4.003268

SUDBURY: 5 HOUR TEMPERATURE STUDY

Temp. Change (Deg. C)	Month	Day	Year	Start Temp. (Deg. C)	Final Temp. (Deg. C)	Rate Temp. Chang (Deg. C / hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -10 C								
15.5	2	2	1954	-16.1	-0.6	3.1	8	32
11.6	2	4	1955	-19.4	-7.8	2.32	6	32
13.3	2	29	1956	-19.4	-6.1	2.66	6	33
13.3	1	2	1957	-30	-16.7	2.66	3	42
15.6	1	12	1958	-18.9	-3.3	3.12	8	34
13.9	12	18	1958	-18.3	-4.4	2.78	8	34
15.6	3	16	1960	-16.7	-1.1	3.12	8	29
11.6	2	26	1961	-13.3	-1.7	2.32	6	24
15	3	10	1962	-12.2	2.8	3	6	24
13.9	3	14	1963	-21.1	-7.2	2.78	8	34
15.6	2	17	1964	-16.7	-1.1	3.12	8	30
13.9	3	25	1965	-16.7	-2.8	2.78	8	28
12.2	12	7	1965	-15	-2.8	2.44	7	27
12.8	2	19	1967	-25.6	-12.8	2.56	10	37
12.3	2	24	1968	-20.6	-8.3	2.46	7	32
13.3	3	2	1969	-12.2	1.1	2.66	6	24
12.8	2	4	1970	-30.6	-17.8	2.56	9	41
15	3	10	1971	-21.7	-6.7	3	8	35
12.8	1	16	1972	-22.8	-10	2.56	7	33
12.2	2	17	1973	-24.4	-12.2	2.44	9	36
11.7	2	25	1974	-20.6	-8.9	2.34	7	31
13.9	3	15	1975	-16.1	-2.2	2.78	8	27
13.9	1	31	1976	-22.2	-8.3	2.78	8	34
15.9	1	18	1977	-28.6	-12.7	3.18	11	43
12.4	2	20	1978	-21.4	-9	2.48	7	32
12.7	2	18	1979	-29.5	-16.8	2.54	10	41
13.9	3	2	1980	-24	-10.1	2.78	10	37
13.8	12	17	1980	-18.5	-4.7	2.76	8	33
12.5	1	23	1982	-16.1	-3.6	2.5	7	27
13.7	2	26	1983	-18.4	-4.7	2.74	7	33
11.2	3	17	1984	-19.9	-8.7	2.24	7	31
12.6	3	6	1985	-16.7	-4.1	2.52	8	27
11.9	1	8	1986	-20.3	-8.4	2.38	6	32
14.9	2	5	1987	-17.7	-2.8	2.98	8	28
13.3	3	22	1988	-20.7	-7.4	2.66	8	33
12.2	2	24	1989	-20.5	-8.3	2.44	7	32
9.7	12	7	1989	-24.4	-14.7	1.94	8	34
						Avg. Press.	7.72972	32.32432
						Std. Dev.	1.20019	4.702236

SUDBURY: 5 HOUR TEMPERATURE STUDY

Temp. Change (Deg. C)	Month	Day	Year	Start Temp. (Deg. C)	Final Temp. (Deg. C)	Rate Temp. Chang (Deg. C / hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -20								
12.2	2	13	1954	-21.1	-8.9	2.44	7	32
10.6	3	8	1955	-20	-9.4	2.12	7	31
12.8	3	17	1956	-20	-7.2	2.56	8	32
13.3	1	2	1957	-30	-16.7	2.66	11	42
13.9	1	12	1958	-20.6	-6.7	2.78	8	33
13.4	3	18	1959	-20.6	-7.2	2.68	8	33
13.4	3	8	1960	-20.6	-7.2	2.68	8	33
11.1	1	23	1961	-27.2	-16.1	2.22	8	36
11.7	2	2	1962	-26.7	-15	2.34	8	36
13.9	3	14	1963	-21.1	-7.2	2.78	8	34
11.7	2	10	1964	-22.8	-11.1	2.34	6	34
10	3	21	1965	-21.7	-11.7	2	6	30
9.5	1	29	1966	-27.8	-18.3	1.9	8	34
12.8	2	19	1967	-25.6	-12.8	2.56	10	37
12.3	2	24	1968	-20.6	-8.3	2.46	7	32
12.3	3	7	1969	-20.6	-8.3	2.46	7	32
12.8	2	4	1970	-30.6	-17.8	2.56	9	41
15	3	10	1971	-21.7	-6.7	3	8	35
12.8	1	16	1972	-22.8	-10	2.56	7	33
12.2	2	17	1973	-24.4	-12.2	2.44	9	36
11.7	2	25	1974	-20.6	-8.9	2.34	7	31
12.2	2	2	1975	-22.8	-10.6	2.44	7	32
13.9	1	31	1976	-22.2	-8.3	2.78	8	34
15.9	1	18	1977	-28.6	-12.7	3.18	11	43
12.4	2	20	1978	-21.4	-9	2.48	7	32
12.7	2	18	1979	-29.5	-16.8	2.54	10	41
13.9	3	2	1980	-24	-10.1	2.78	10	37
11.7	12	17	1980	-27.4	-15.7	2.34	10	36
12.3	1	27	1982	-21.5	-9.2	2.46	7	32
11.8	1	4	1983	-20.4	-8.6	2.36	7	32
11	2	1	1984	-20	-9	2.2	7	31
11.7	12	25	1984	-24.5	-12.8	2.34	8	35
11.9	1	8	1986	-20.3	-8.4	2.38	6	32
11.7	2	9	1987	-20.6	-8.9	2.34	7	31
13.3	3	22	1988	-20.7	-7.4	2.66	8	33
12.2	2	24	1989	-20.5	-8.3	2.44	7	32
9.7	12	7	1989	-24.4	-14.7	1.94	8	34
						Avg. Press.	7.91891	34.16216
						Std. Dev.	1.28143	3.183687

SUDBURY: 5 HOUR TEMPERATURE STUDY

Temp. Change (Deg. C)	Month	Day	Year	Start Temp. (Deg. C)	Final Temp. (Deg. C)	Rate Temp. Chang (Deg. C / hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -30 C								
10	2	12	1954	-30	-20	2	8	39
7.3	1	30	1955	-30.6	-23.3	1.46	7	37
6.7	12	20	1955	-31.7	-25	1.34	4	36
13.3	1	2	1957	-30	-16.7	2.66	11	42
0								
8.9	1	5	1959	-35	-26.1	1.78	8	40
6.1	1	9	1960	-32.2	-26.1	1.22	4	35
10.6	1	25	1961	-30	-19.4	2.12	8	40
9.5	2	10	1962	-31.7	-22.2	1.9	8	39
8.3	1	15	1963	-30	-21.7	1.66	8	38
5.5	12	30	1963	-31.1	-25.6	1.1	4	35
7.8	1	29	1965	-35	-27.2	1.56	8	38
7.2	2	18	1966	-30	-22.8	1.44	6	37
10.6	2	7	1967	-30	-19.4	2.12	8	40
10	1	11	1968	-31.1	-21.1	2	8	39
6.1	12	25	1968	-30	-23.9	1.22	5	35
12.8	2	4	1970	-30.6	-17.8	2.56	10	41
10	2	2	1971	-33.3	-23.3	2	9	40
8.3	1	16	1972	-31.1	-22.8	1.66	8	38
10	2	16	1973	-30	-20	2	8	39
7.8	2	2	1974	-30	-22.2	1.56	7	38
10	1	20	1975	-30.6	-20.6	2	8	40
10.6	1	24	1976	-30.6	-20	2.12	8	40
14.3	1	18	1977	-31.4	-17.1	2.86	12	42
0								
11.1	2	6	1979	-30.3	-19.2	2.22	8	40
0								
8.8	1	12	1981	-30	-21.2	1.76	8	40
10	1	18	1982	-31.8	-21.8	2	8	40
0								
9.6	1	12	1984	-30	-20.4	1.92	8	39
0								
7.9	12	18	1985	-32.5	-24.6	1.58	5	36
4.9	1	24	1987	-30.3	-25.4	0.98	4	32
11	1	14	1988	-30.3	-19.3	2.2	8	40
8.2	1	4	1989	-30	-21.8	1.64	7	38
5.7	12	21	1989	-30.4	-24.7	1.14	4	35
						Avg. Press.	7.34375	38.375
						Std. Dev.	1.94630	2.260392

SUDBURY: 10 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -10 C								
17.3	2	17	1954	-10.6	6.7	1.73	6	17
15	2	13	1955	-27.8	-12.8	1.5	12	32
15	3	17	1956	-20	-5	1.5	12	26
16.7	1	2	1957	-30	-13.3	1.67	15	38
18.9	1	12	1958	-22.2	-3.3	1.89	14	29
17.8	12	22	1958	-21.7	-3.9	1.78	13	28
16.6	3	16	1960	-17.2	-0.6	1.66	10	25
16.7	3	11	1961	-22.8	-6.1	1.67	13	27
16.7	3	10	1962	-12.8	3.9	1.67	7	22
17.7	3	19	1963	-19.4	-1.7	1.77	13	28
16.7	2	22	1964	-21.7	-5	1.67	12	27
18.3	1	21	1965	-22.2	-3.9	1.83	13	28
13.9	3	16	1966	-13.3	0.6	1.39	9	18
18.3	1	9	1967	-26.1	-7.8	1.83	16	33
14.5	3	3	1968	-17.8	-3.3	1.45	10	24
14.5	4	3	1969	-12.8	1.7	1.45	7	21
17.2	2	4	1970	-31.1	-13.9	1.72	13	38
15	3	10	1971	-21.7	-6.7	1.5	12	25
18.8	1	16	1972	-29.4	-10.6	1.88	16	39
15	2	13	1973	-20	-5	1.5	12	25
15	3	29	1974	-14.4	0.6	1.5	10	23
17.8	1	23	1975	-21.7	-3.9	1.78	13	28
18.3	1	31	1976	-23.3	-5	1.83	15	32
21.6	1	18	1977	-31.4	-9.8	2.16	17	40
14.9	3	5	1978	-21.2	-6.3	1.49	12	25
16.3	2	26	1979	-17.5	-1.2	1.63	10	26
14.9	3	19	1980	-11.5	3.4	1.49	7	17
23.9	12	17	1980	-28.6	-4.7	2.39	20	40
16.5	3	28	1982	-16.6	-0.1	1.65	11	25
17.8	12	13	1982	-21	-3.2	1.78	13	28
15.1	12	8	1983	-19.9	-4.8	1.51	12	25
17	12	7	1984	-21.2	-4.2	1.7	13	27
17	1	8	1986	-24.5	-7.5	1.7	13	28
16.5	2	5	1987	-19.3	-2.8	1.65	12	26
18.9	3	5	1988	-19.5	-0.6	1.89	14	29
18	1	21	1989	-25.4	-7.4	1.8	14	33
15.4	11	29	1989	-22.1	-6.7	1.54	12	26
						Avg.	12.24324	27.78378
						Std.Dev.	2.822739	5.771013

SUDBURY: 10 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -20 C								
14.5	2	13	1954	-22.8	-8.3	1.45	12	25
15	2	13	1955	-27.8	-12.8	1.5	12	33
15	3	17	1956	-20	-5	1.5	12	26
16.7	1	2	1957	-30	-13.3	1.67	15	38
18.9	1	12	1958	-22.2	-3.3	1.89	14	29
17.8	12	22	1958	-21.7	-3.9	1.78	13	28
16.1	3	7	1960	-22.2	-6.1	1.61	12	27
16.7	3	11	1961	-22.8	-6.1	1.67	13	27
15	3	3	1962	-25	-10	1.5	12	32
17.3	3	14	1963	-20.6	-3.3	1.73	12	27
16.7	2	22	1964	-21.7	-5	1.67	12	27
18.3	1	21	1965	-22.2	-3.9	1.83	13	28
11.1	1	26	1966	-28.3	-17.2	1.11	9	34
18.3	1	9	1967	-26.1	-7.8	1.83	16	34
12.8	2	16	1968	-20	-7.2	1.28	11	23
14.4	3	7	1969	-20	-5.6	1.44	12	24
17.2	2	4	1970	-31.1	-13.9	1.72	13	38
15	3	10	1971	-21.7	-6.7	1.5	12	25
18.8	1	16	1972	-29.4	-10.6	1.88	16	39
15	2	13	1973	-20	-5	1.5	12	25
13.4	2	18	1974	-20.6	-7.2	1.34	11	23
17.8	1	23	1975	-21.7	-3.9	1.78	13	28
18.3	1	31	1976	-23.3	-5	1.83	15	32
21.6	1	18	1977	-31.4	-9.8	2.16	17	40
14.9	3	5	1978	-21.2	-6.3	1.49	12	25
16.3	3	15	1979	-24.5	-8.2	1.63	13	28
14.7	3	2	1980	-23.2	-8.5	1.47	11	27
23.9	12	17	1980	-28.6	-4.7	2.39	20	40
16.3	1	19	1982	-27.3	-11	1.63	12	33
17.8	12	13	1982	-21	-3.2	1.78	13	28
15	12	20	1983	-32	-17	1.5	14	36
17	12	7	1984	-21.2	-4.2	1.7	13	27
17	1	8	1986	-24.5	-7.5	1.7	13	28
16	2	9	1987	-22.4	-6.4	1.6	12	27
16.5	3	22	1988	-20.1	-3.6	1.65	13	27
18	1	21	1989	-25.4	-7.4	1.8	14	33
15.4	11	29	1989	-22.1	-6.7	1.54	12	26
						Avg.	13	29.64864
						Std.Dev.	1.917205	4.850278

SUDBURY: 10 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -30 C								
13.9	2	12	1954	-30	-16.1	1.39	14	36
7.3	1	30	1955	-30.6	-23.3	0.73	9	30
6.1	12	20	1955	-31.7	-25.6	0.61	5	29
16.7	1	2	1957	-30	-13.3	1.67	15	38
0								
11.1	1	5	1959	-35	-23.9	1.11	10	35
9.4	1	9	1960	-33.3	-23.9	0.94	9	32
14.4	1	23	1961	-30	-15.6	1.44	14	36
13.3	1	29	1962	-34.4	-21.1	1.33	11	34
8.9	1	15	1963	-30	-21.1	0.89	9	32
12.2	12	30	1963	-31.1	-18.9	1.22	10	34
12.8	1	29	1965	-35	-22.2	1.28	10	34
10	2	18	1966	-31.1	-21.1	1	9	33
14.5	2	7	1967	-31.7	-17.2	1.45	14	36
12.3	1	11	1968	-31.7	-19.4	1.23	9	32
5.6	12	25	1968	-30	-24.4	0.56	5	29
17.2	2	4	1970	-31.1	-13.9	1.72	13	35
11.1	1	31	1971	-34.4	-23.3	1.11	9	32
17.8	1	16	1972	-31.1	-13.3	1.78	15	39
11.7	1	31	1973	-31.7	-20	1.17	10	34
9.4	2	2	1974	-30	-20.6	0.94	9	32
15	1	20	1975	-32.8	-17.8	1.5	10	34
14.5	1	24	1976	-33.9	-19.4	1.45	11	34
21.6	1	18	1977	-31.4	-9.8	2.16	17	40
0								
15.4	2	18	1979	-30.8	-15.4	1.54	14	36
0								
11.9	12	17	1980	-30.4	-18.5	1.19	10	34
14.9	1	10	1982	-37.5	-22.6	1.49	15	39
0								
15	12	20	1983	-32	-17	1.5	14	36
0								
10.3	12	18	1985	-34.7	-24.4	1.03	10	34
12.2	1	24	1987	-30.7	-18.5	1.22	10	34
14.8	1	14	1988	-32.6	-17.8	1.48	14	36
17.6	2	9	1989	-30	-12.4	1.76	15	39
9.5	12	21	1989	-30.4	-20.9	0.95	9	32
						Avg.	10.84848	34.375
						Std.Dev.	3.438826	2.735758

SUDBURY: 20 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp. (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -10 C								
15.6	2	14	1954	-22.8	-7.2	0.78	14	23
19.5	12	23	1954	-22.8	-3.3	0.975	17	24
15	12	2	1955	-16.7	-1.7	0.75	14	19
24.4	12	19	1956	-27.2	-2.8	1.22	23	30
20.5	1	13	1958	-22.2	-1.7	1.025	18	26
21.1	12	23	1958	-21.7	-0.6	1.055	18	25
17.8	2	9	1960	-18.9	-1.1	0.89	16	23
20.6	12	14	1960	-25.6	-5	1.03	19	28
18.3	1	2	1962	-23.9	-5.6	0.915	18	27
16.7	1	29	1963	-27.8	-11.1	0.835	14	27
20	3	7	1964	-22.2	-2.2	1	18	24
19.5	1	21	1965	-22.8	-3.3	0.975	17	24
18.9	1	3	1966	-18.9	0	0.945	17	23
20.6	2	10	1967	-23.9	-3.3	1.03	17	24
15.6	1	26	1968	-25	-9.4	0.78	14	26
16.2	12	1	1968	-15.6	0.6	0.81	13	19
20.6	1	31	1970	-27.8	-7.2	1.03	18	32
16.7	1	21	1971	-21.1	-4.4	0.835	14	23
26.1	1	1	1972	-27.8	-1.7	1.305	23	31
19.4	12	18	1972	-24.4	-5	0.97	19	27
18.3	12	25	1973	-16.1	2.2	0.915	14	19
25	1	21	1975	-32.2	-7.2	1.25	23	35
24.4	1	19	1976	-31.1	-6.7	1.22	23	35
23.9	12	14	1976	-23.9	0	1.195	22	29
14.1	12	28	1977	-24.3	-10.2	0.705	14	25
17.6	2	20	1979	-27.8	-10.2	0.88	14	27
18.1	11	17	1979	-15.2	2.9	0.905	13	19
28.9	12	18	1980	-30.4	-1.5	1.445	25	35
19.8	1	11	1982	-38.4	-18.6	0.99	19	34
25.5	1	4	1983	-25.2	0.3	1.275	23	30
18.3	1	22	1984	-30.5	-12.2	0.915	17	32
23.8	12	8	1984	-25.1	-1.3	1.19	22	30
21.1	1	9	1986	-27.1	-6	1.055	19	29
19.8	12	14	1986	-26.2	-6.4	0.99	18	29
22.5	2	22	1988	-27.5	-5	1.125	20	33
23.3	1	12	1989	-23.1	0.2	1.165	23	29
17.1	11	30	1989	-23.2	-6.1	0.855	17	25
						Avg.	18.02702	27.02702
						Std.Dev.	3.397029	4.523132

SUDBURY: 20 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp. (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -20 C								
15.6	2	14	1954	-22.8	-7.2	0.78	14	23
19.5	12	23	1954	-22.8	-3.3	0.975	17	24
15	12	24	1955	-26.1	-11.1	0.75	14	26
24.4	12	19	1956	-27.2	-2.8	1.22	23	30
20.5	1	13	1958	-22.2	-1.7	1.025	18	26
21.1	12	23	1958	-21.7	-0.6	1.055	18	25
15	2	16	1960	-20.6	-5.6	0.75	14	22
20.6	12	14	1960	-25.6	-5	1.03	19	28
18.3	1	2	1962	-23.9	-5.6	0.915	18	27
16.7	1	29	1963	-27.8	-11.1	0.835	14	27
20	3	7	1964	-22.2	-2.2	1	18	24
19.5	1	21	1965	-22.8	-3.3	0.975	17	24
13.9	1	9	1966	-20	-6.1	0.695	13	21
20.6	2	10	1967	-23.9	-3.3	1.03	17	24
15.6	1	26	1968	-25	-9.4	0.78	14	26
13.3	1	28	1969	-20	-6.7	0.665	13	21
20.6	1	31	1970	-27.8	-7.2	1.03	18	32
16.7	1	21	1971	-21.1	-4.4	0.835	14	23
26.1	1	1	1972	-27.8	-1.7	1.305	23	31
19.4	12	18	1972	-24.4	-5	0.97	19	27
15.6	1	14	1974	-20.6	-5	0.78	14	1[illegible]
25	1	21	1975	-32.2	-7.2	1.25	23	35
24.4	1	19	1976	-31.1	-6.7	1.22	23	35
23.9	12	14	1976	-23.9	0	1.195	22	29
14.1	12	28	1977	-24.3	-10.2	0.705	14	25
17.6	2	20	1979	-27.8	-10.2	0.88	14	27
14.4	2	27	1980	-27.1	-12.7	0.72	14	25
28.9	12	18	1980	-30.4	-1.5	1.445	25	35
19.8	1	11	1982	-38.4	-18.6	0.99	19	34
25.5	1	4	1983	-25.2	0.3	1.275	23	30
18.3	1	22	1984	-30.5	-12.2	0.915	17	32
23.8	12	8	1984	-25.1	-1.3	1.19	22	30
21.1	1	9	1986	-27.1	-6	1.055	19	29
19.8	12	14	1986	-26.2	-6.4	0.99	18	29
22.5	2	22	1988	-27.5	-5	1.125	20	33
23.3	1	12	1989	-23.1	0.2	1.165	23	29
17.1	11	30	1989	-23.2	-6.1	0.855	17	25
						Avg.	17.89189	27.35135
						Std.Dev.	3.501225	4.127797

SUDBURY: 20 HOUR TEMPERATURE STUDY

Temp. Diff (Deg. C)	Month	Day	Year	Start Temp. (Deg. C)	Fin. T. (Deg. C)	T rate (C/hr.)	D and M Kips/ft	Lindgren Kips/ft
Start Temp. < -30 C								
10	2	13	1954	-30	-20	0.5	9	27
10.6	1	31	1955	-30	-19.4	0.53	9	27
4.4	12	21	1955	-31.1	-26.7	0.22	5	21
15	12	31	1956	-32.2	-17.2	0.75	14	30
0								
10	12	22	1958	-30	-20	0.5	9	27
12.8	1	10	1960	-32.2	-19.4	0.64	9	29
8.3	1	24	1961	-30	-21.7	0.415	9	25
15.6	2	2	1962	-30	-14.4	0.78	14	31
8.3	2	4	1963	-32.2	-23.9	0.415	8	25
15.5	12	31	1963	-31.1	-15.6	0.775	14	30
15.6	1	30	1965	-35.6	-20	0.78	14	30
10	1	16	1966	-30	-20	0.5	9	27
13.3	1	19	1967	-34.4	-21.1	0.665	10	30
11.7	1	9	1968	-30.6	-18.9	0.585	9	28
4.4	12	26	1968	-30	-25.6	0.22	5	21
17.3	2	5	1970	-30.6	-13.3	0.865	15	32
10	1	19	1971	-30.6	-20.6	0.5	9	27
23.9	1	17	1972	-32.2	-8.3	1.195	18	35
13.4	2	1	1973	-31.7	-18.3	0.67	10	30
6.2	2	3	1974	-30.6	-24.4	0.31	5	24
25	1	21	1975	-32.2	-7.2	1.25	23	35
24.4	1	19	1976	-31.1	-6.7	1.22	23	35
22.7	1	18	1977	-31.7	-9	1.135	18	35
0								
13 5	2	7	1979	-30.7	-17.2	0.675	10	30
0								
28.9	12	18	1980	-30.4	-1.5	1.445	26	35
19.8	1	11	1982	-38.4	-18.6	0.99	19	34
0								
18.3	1	22	1984	-30.5	-12.2	0.915	17	32
0								
13.1	12	19	1985	-34.7	-21.6	0.655	14	32
11.3	1	24	1987	-30.6	-19.3	0.565	9	28
21.5	1	15	1988	-30.3	-8.8	1.075	18	33
15.8	2	10	1989	-30.1	-14.3	0.79	14	30
0.799999	12	22	1989	-30.4	-29.6	0.04		
						Avg.	12.74193	29.51612
						Std.Dev.	5.363364	3.842638